Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment

Canadian Association of Physicists Congress, May 27th-31st 2024

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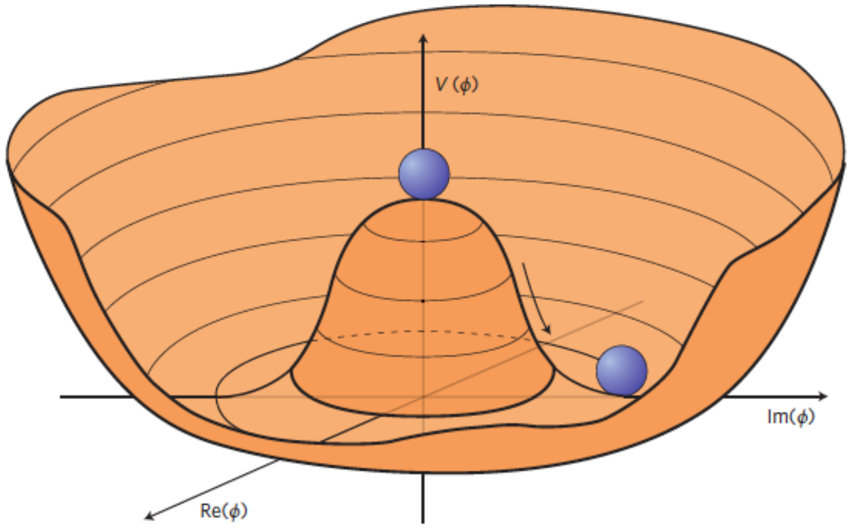
Introduction (1)

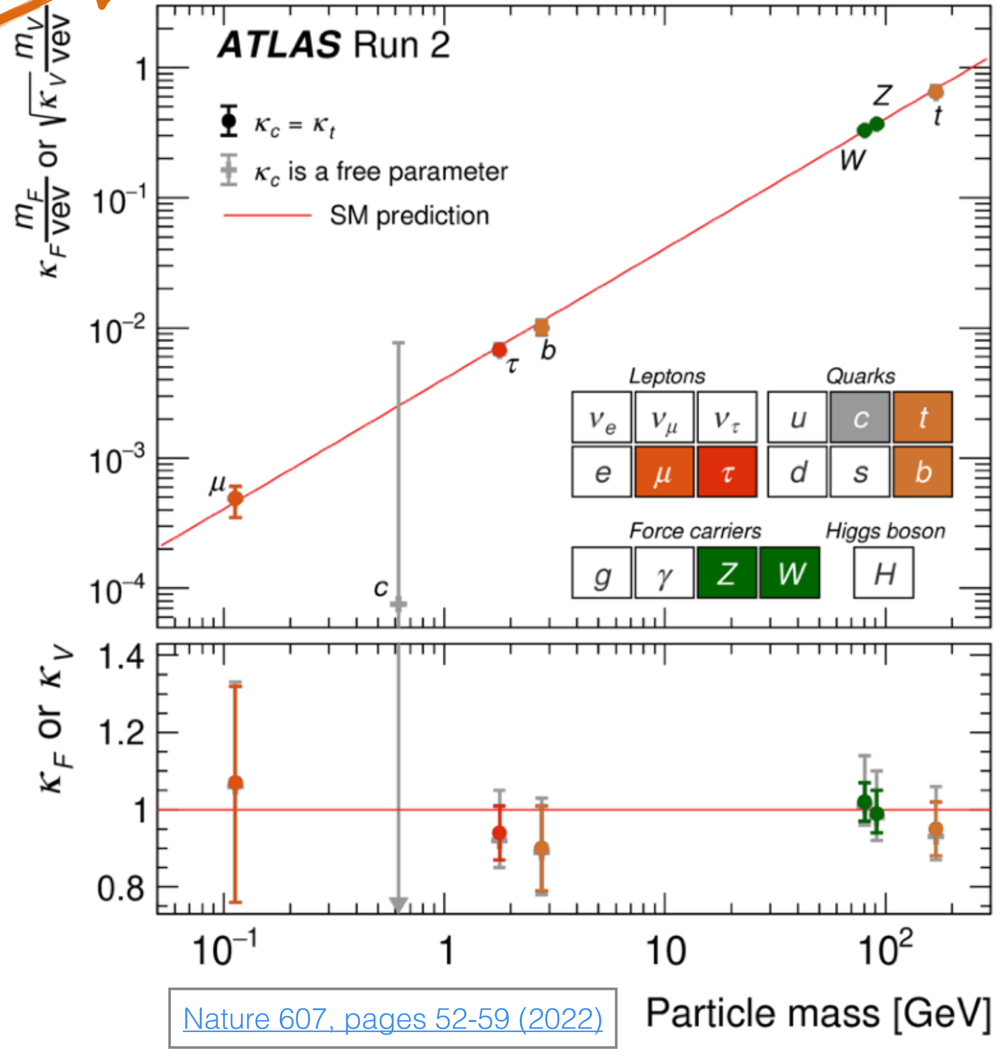
What is the Higgs boson and why its discovery (2012) was important

- Higgs boson: **massive scalar particle generated by the spontaneous breaking** of the electroweak gauge symmetry.
- Ok… but what does this mean? 🙂
  - Take the massless SM lagrangian $\mathscr{L}^{SM}$, add a scalar particle and a "a mexican hat" potential:

$$\boxed{V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2}$$



  - Around the new potential minimum, electroweak bosons (W/Z) and fermions **acquire masses. A massive scalar appears** (the Higgs boson).
- This works surprisingly well (so far)! **All observed couplings (W,Z,b,t,τ) are consistent with the SM Higgs mechanism**!

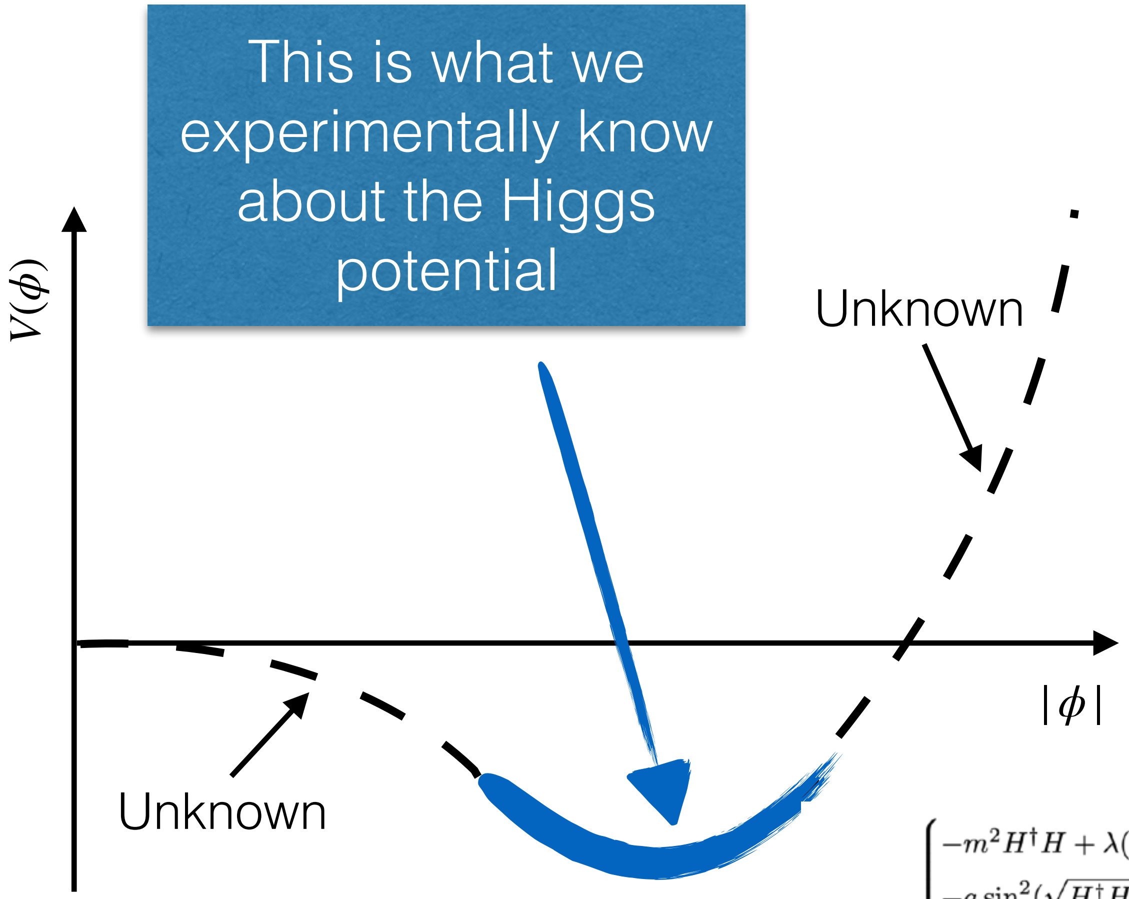


Nature 607, pages 52-59 (2022)

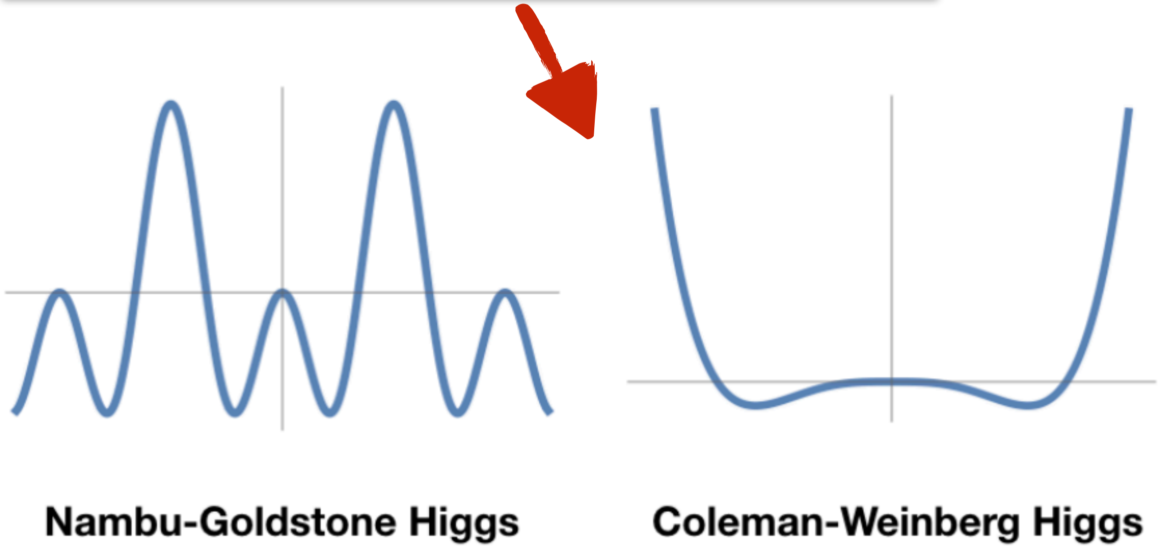
Is this the end of the story?

Have we understood everything about the Higgs?

- Simple answer: **No!**
- The simple existence of the Higgs in the SM is **really unique and puzzling:**
  - Are there **more Higgs bosons**?
  - Why is the **Higgs mass so small**?
  - Is it really **a Mexican hat potential shape or something else?**


This is what we experimentally know about the Higgs potential

Many **different potential shapes could explain the same physics** we see today!



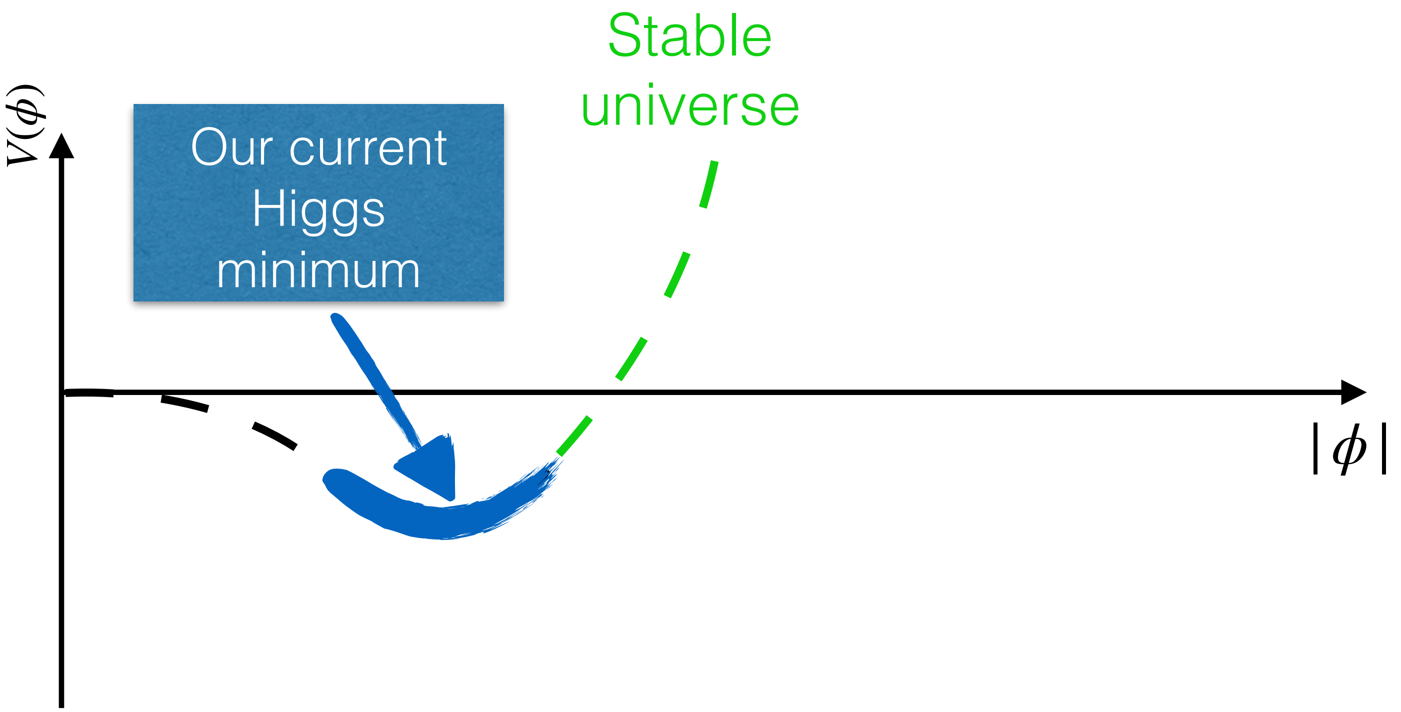
$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

arxiv:1907.02078

The Higgs potential in the history of the universe

Electroweak baryogenesis and vacuum metastability

- The Higgs potential is **deeply related to the baryogenesis problem**.
  - A **potential shape beyond the SM could explain** the overabundance of matter in the universe (EWK baryogenesis)!
- Also, important question about the **stability of our current universe vacuum state!**



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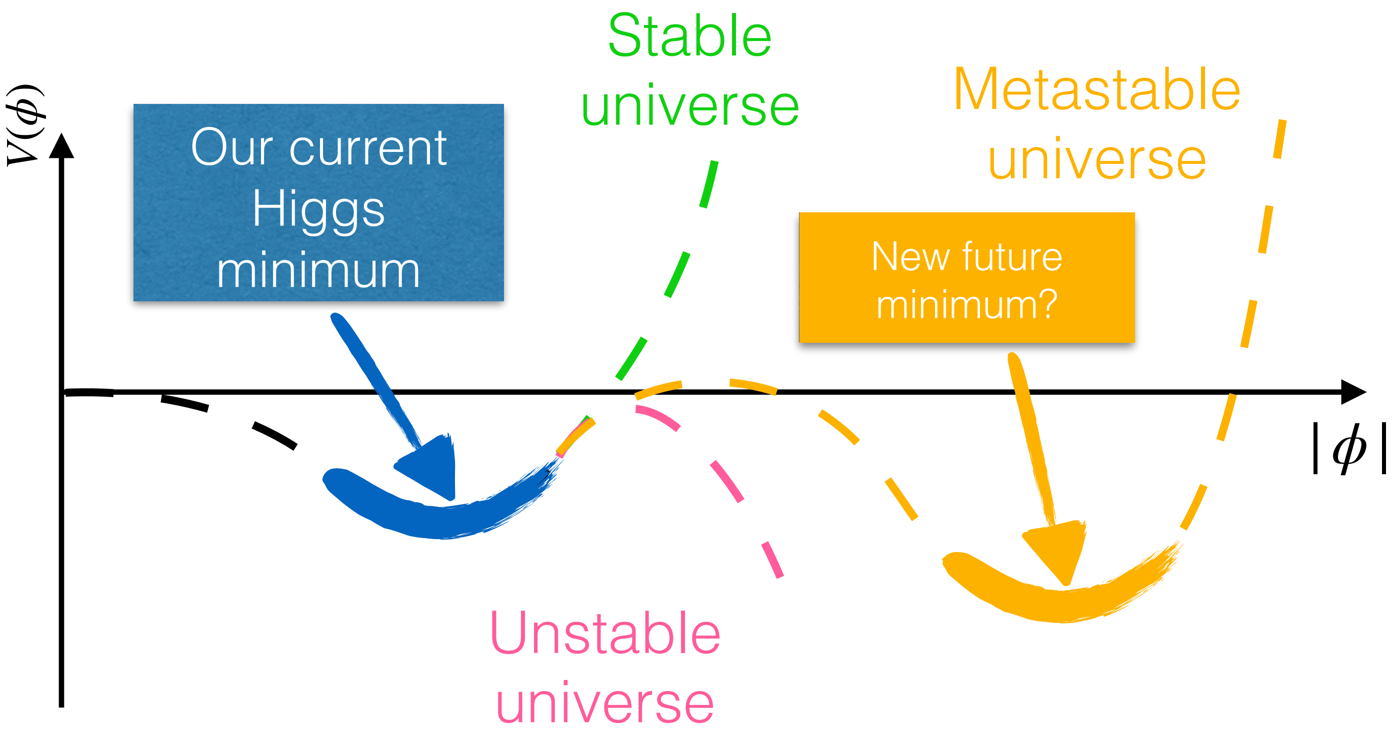

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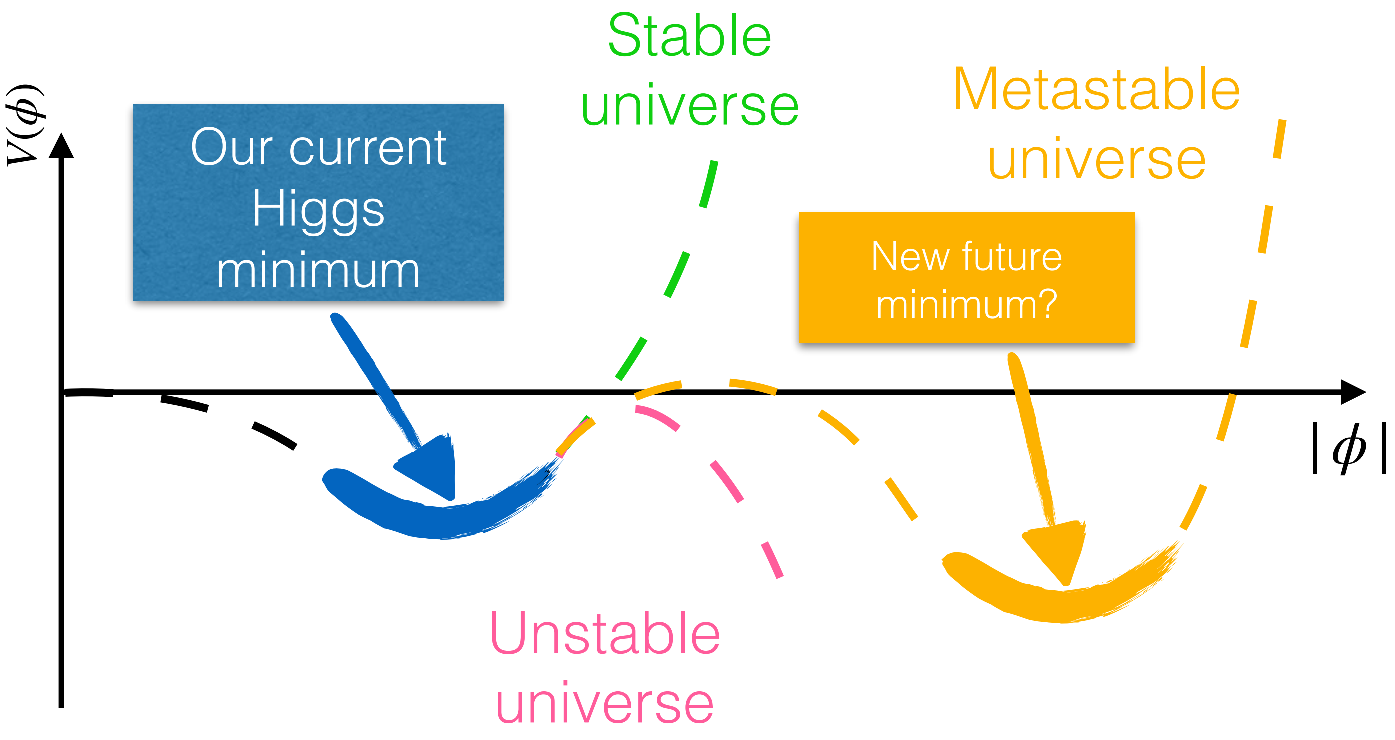
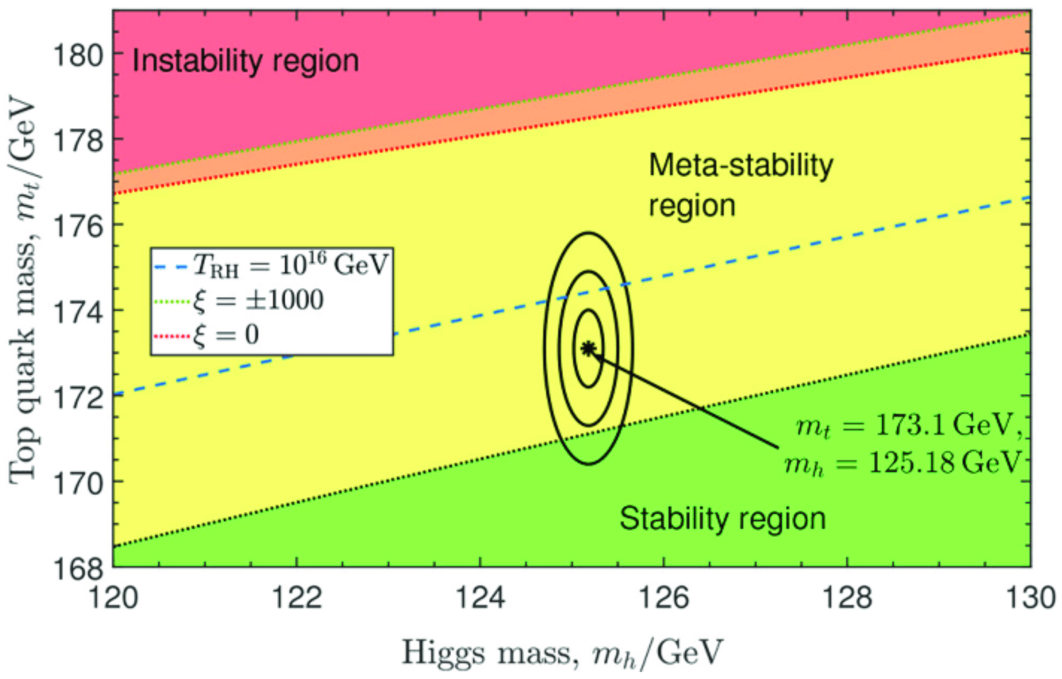


Markannen, Rajantie, Stopyra



Current measurements suggest that we live in a **metastable** universe that will decay in future!

Measuring **the Higgs potential is critical** to fully understand how the **universe started…** and also how it will **finish**.

But so… **how can we measure the Higgs potential?**

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How to measure the Higgs potential

Multiple-Higgs events

We **need to access the λ parameter** of the Higgs potential.

$$\boxed{V(h) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \simeq \frac{1}{2}m_h^2h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots}$$

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Tells us where the minimum of the potential is

$\Rightarrow m_H = \sqrt{2\lambda v} \approx 125$ GeV means $\lambda_{SM} \approx 0.13$

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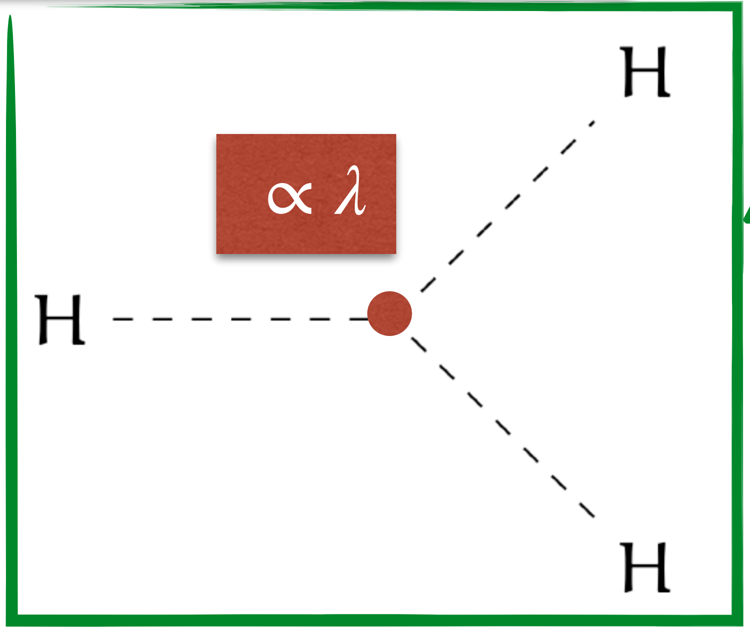
Trilinear Higgs self-coupling



Access to λ through **3-Higgs interactions**

We generally look more at κ_λ rather than λ directly

$$\boxed{\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}}$$

How to measure the Higgs potential

Multiple-Higgs events

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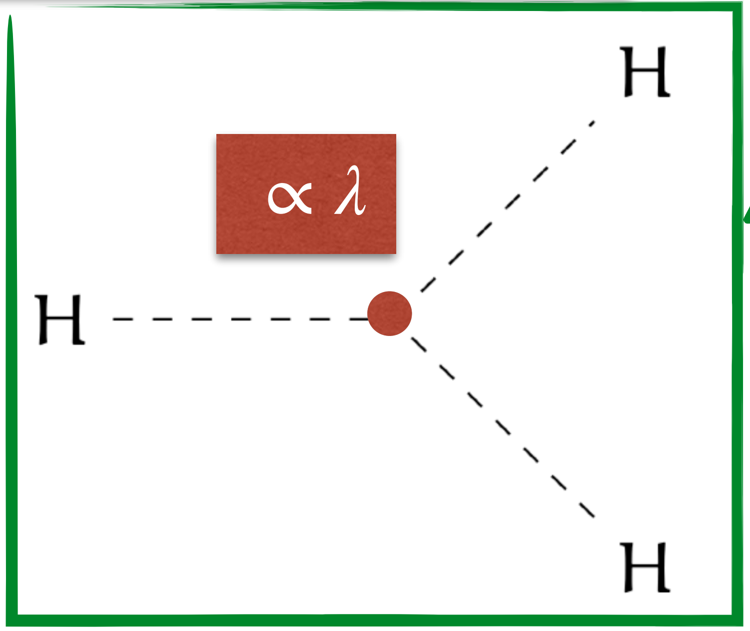
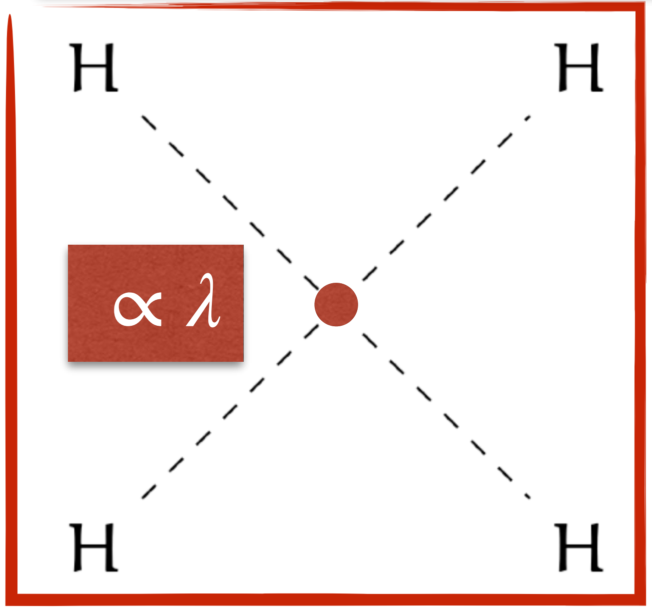


Access to λ through **3-Higgs interactions**

Quadrilinear Higgs self-coupling



Out of the reach of (HL)-LHC (and even most of future collider scenarios)

We generally look more at κ_λ rather than λ directly

$$\boxed{\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}}$$

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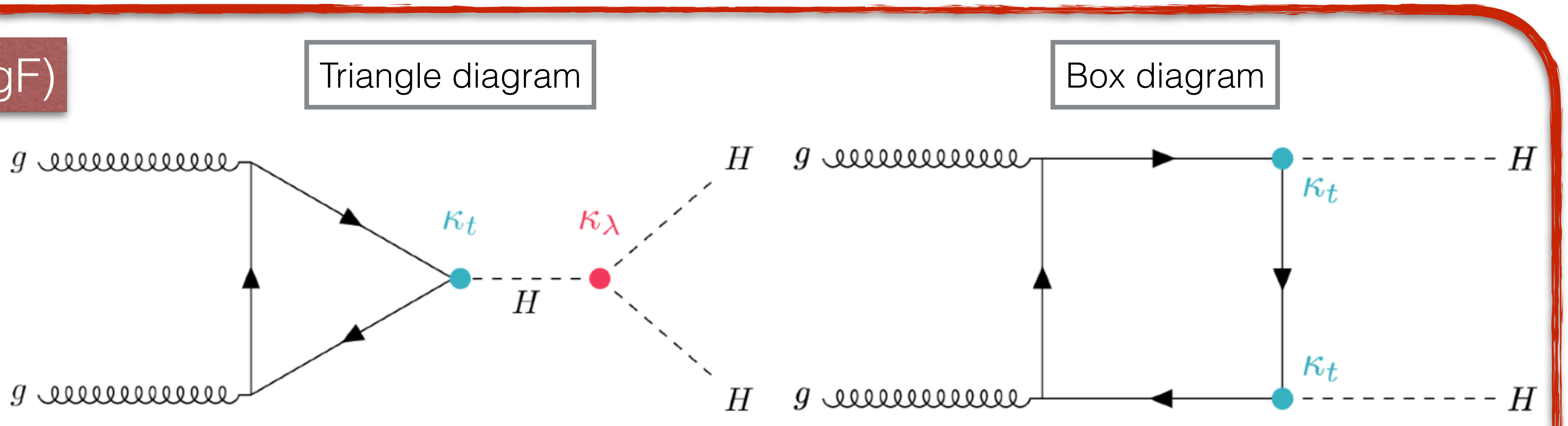
HH production at the LHC

Non-resonant HH production

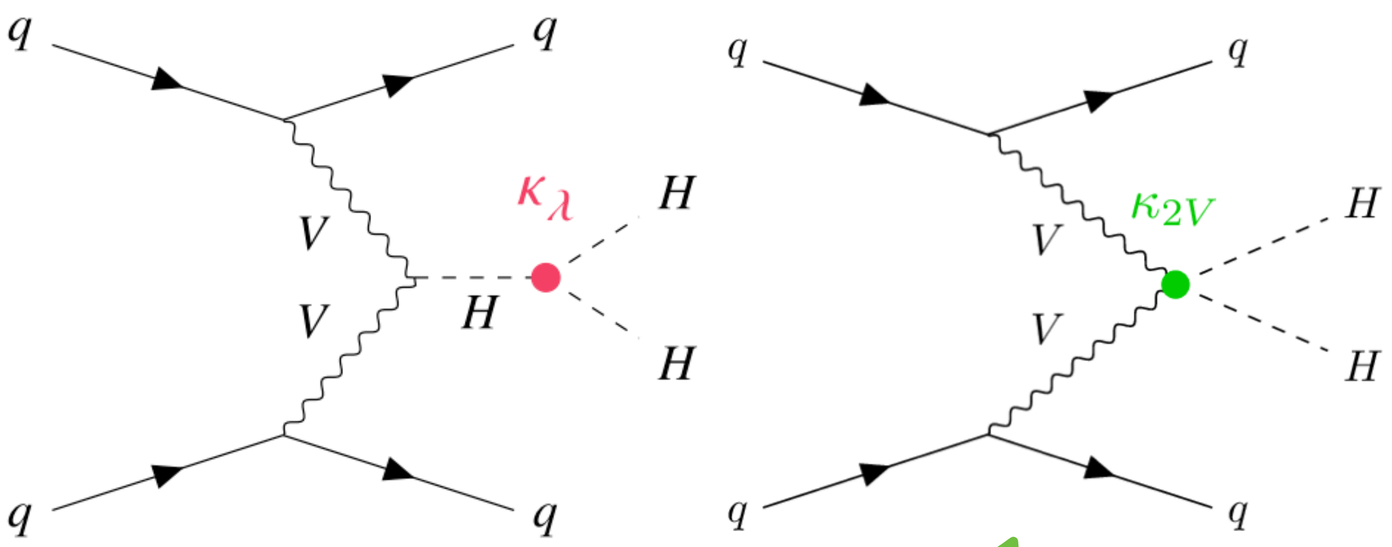
Gluon-gluon fusion (ggF)



- Destructive interference leads to small cross-section:

$\sigma_{\text{ggF}} = 31.05$ fb → 1 HH event every 1000 single-H events!

Vector-boson fusion (VBF)



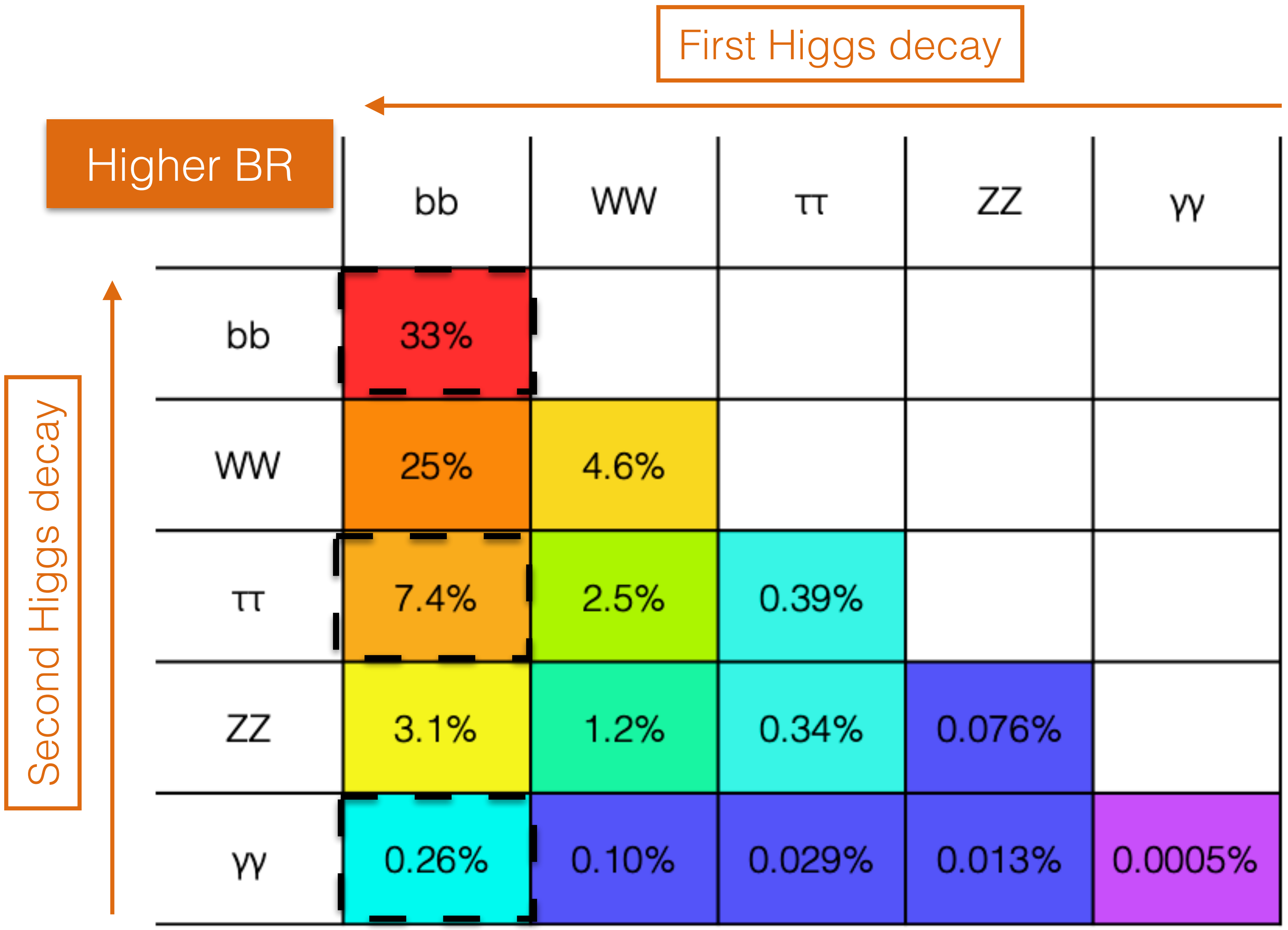
- Signature: 2 Higgs + 2 quarks close to the LHC proton beams.
- Access to κ_λ, but also to **VVHH process** (never measured!) which could provide test **of SM unitarity via measurement of k_{2V}.**
- **Very tiny** cross-section:

$\sigma_{\text{VBF}} = 1.72$ fb

$$\kappa_{2V} \equiv \frac{c_{2V}}{c_{2V}^{SM}}$$

The HH final states

- With $\sigma(HH) \approx 31$ fb and $\mathscr{L}^{int} = 139$ fb^{-1}, **~4k HH events produced** in the LHC Run 2.
  - **Maximal sensitivity requires multiple analysis channels** targeting different decays.



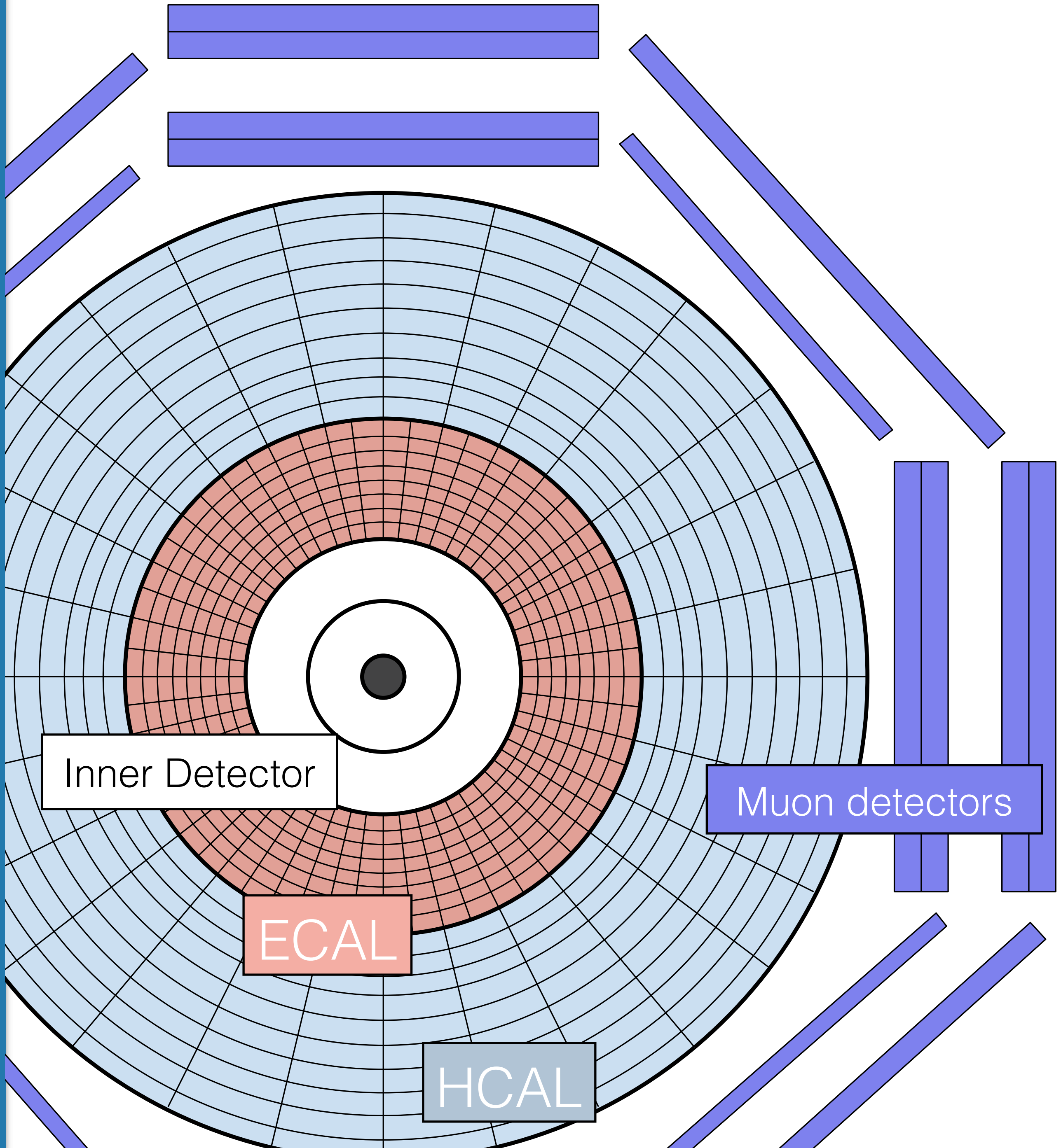
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

⬚ Most sensitive ATLAS channels covered in this talk.

HH detection at ATLAS

HH final state reconstruction

To observe HH decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we **need to identify b-quarks, τ-leptons and photons.**



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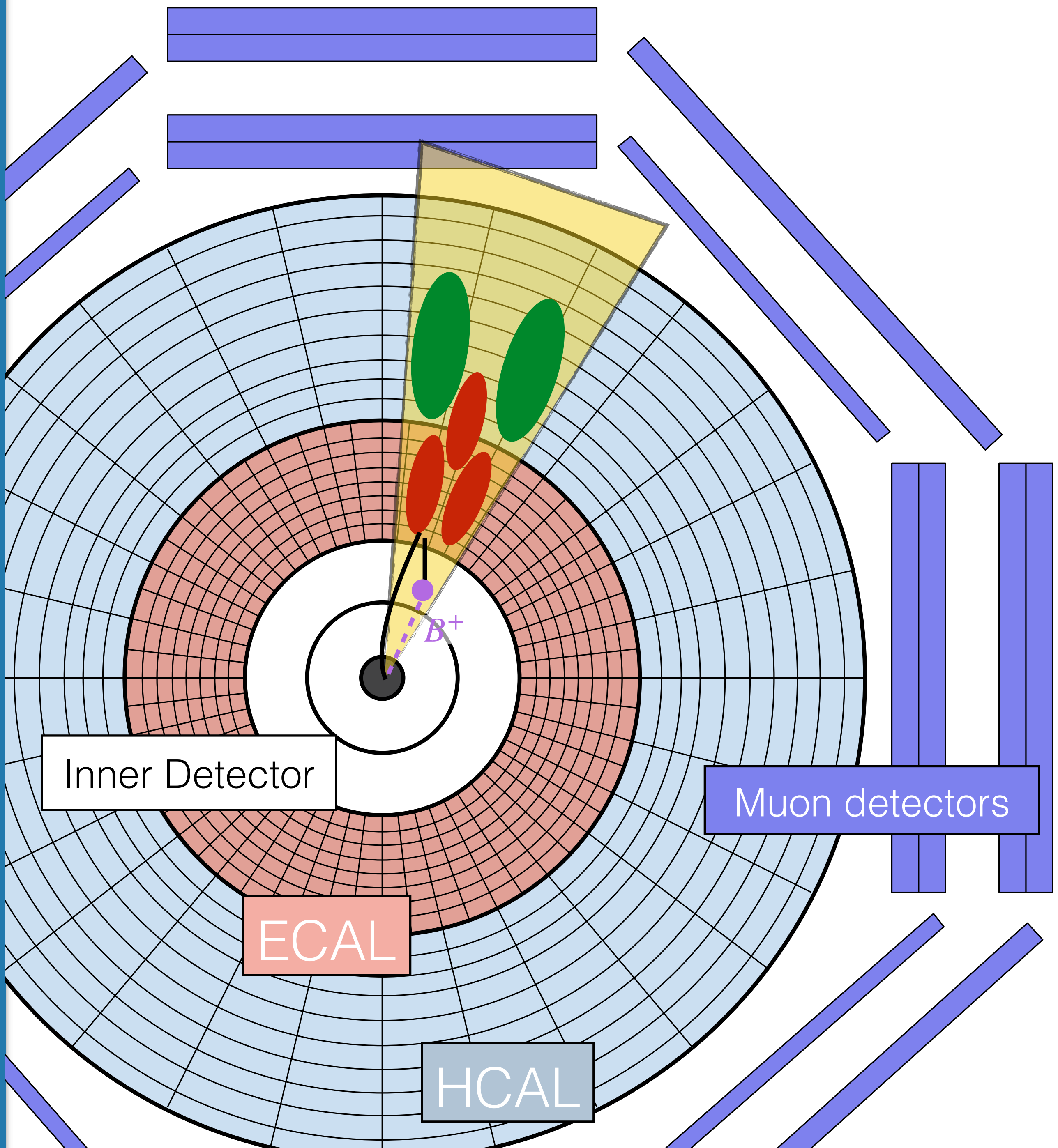

- b-jets: collimated **spray of particles** containing a **displaced vertex** (B-hadron decay).
  - Machine Learning **b-tagging algorithms** for identification.

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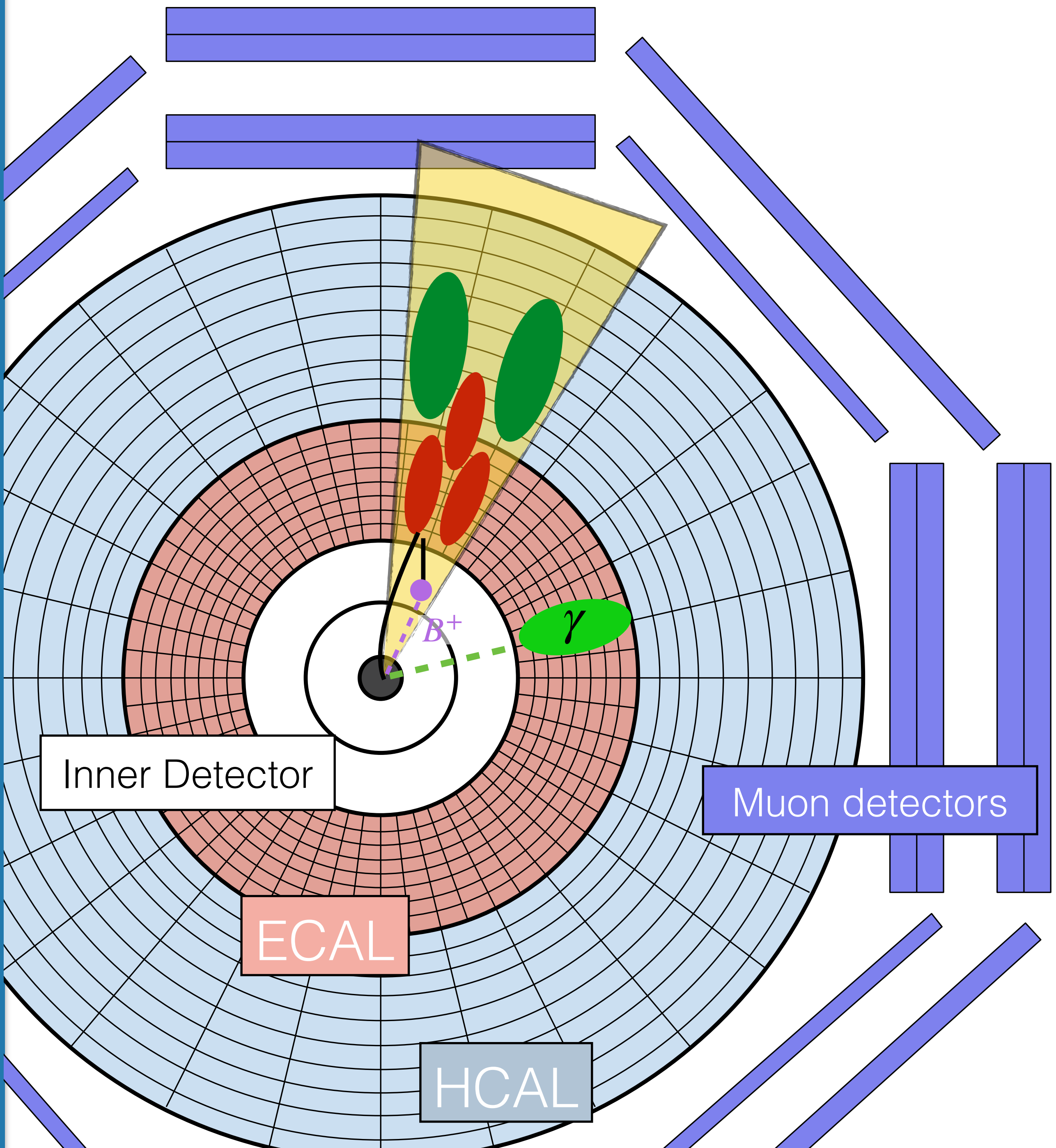

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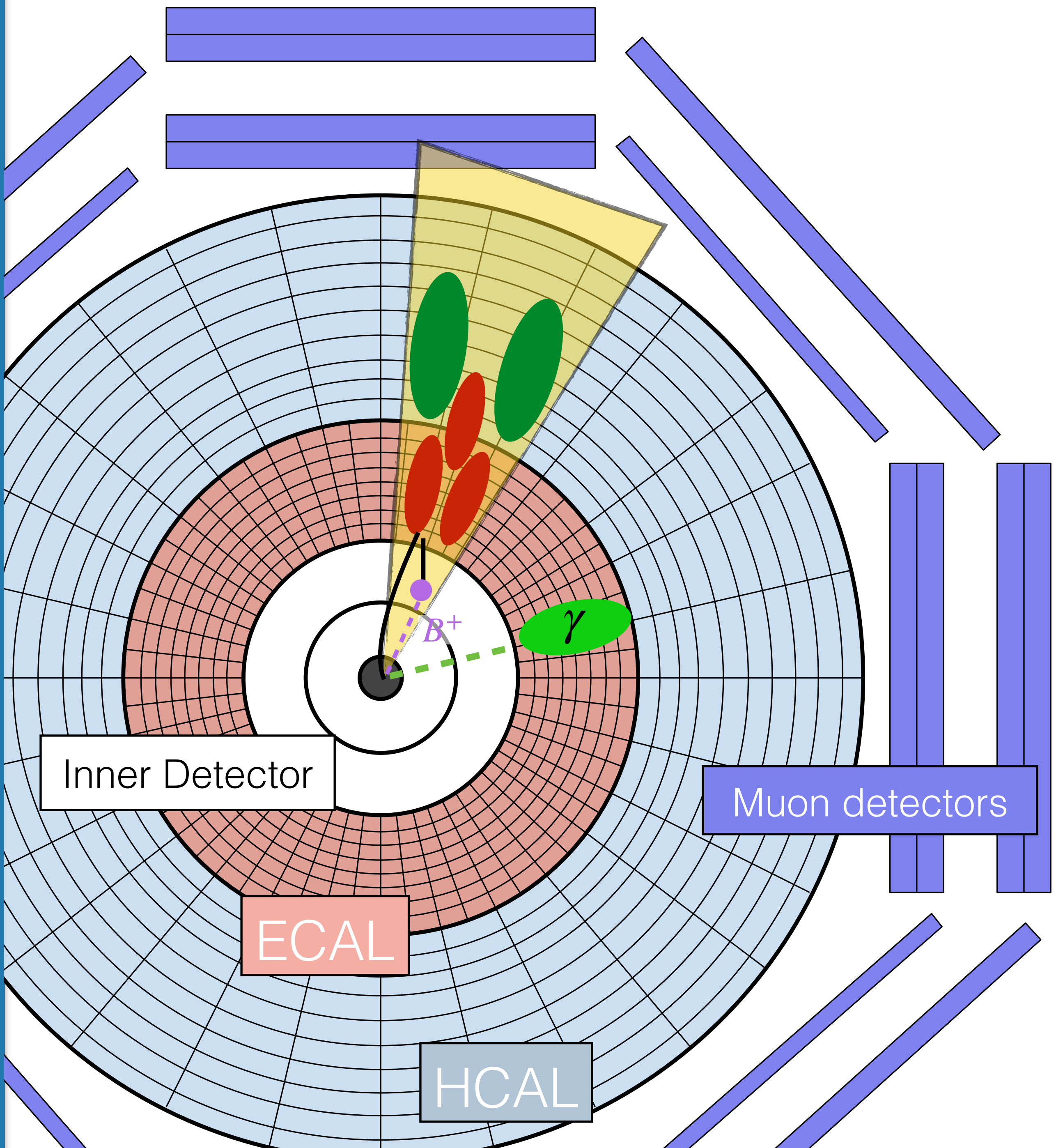

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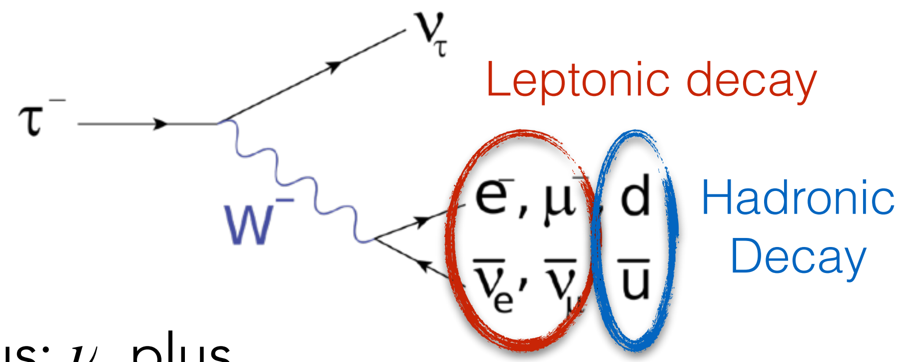

- Taus: ν_τ plus
    1. Hadronic τ (τ_{had}): **jet** with low number of tracks identified with τ tagger.
    2. Leptonic τ (τ_{lep}): **muon** (μ) or **electron** (e)

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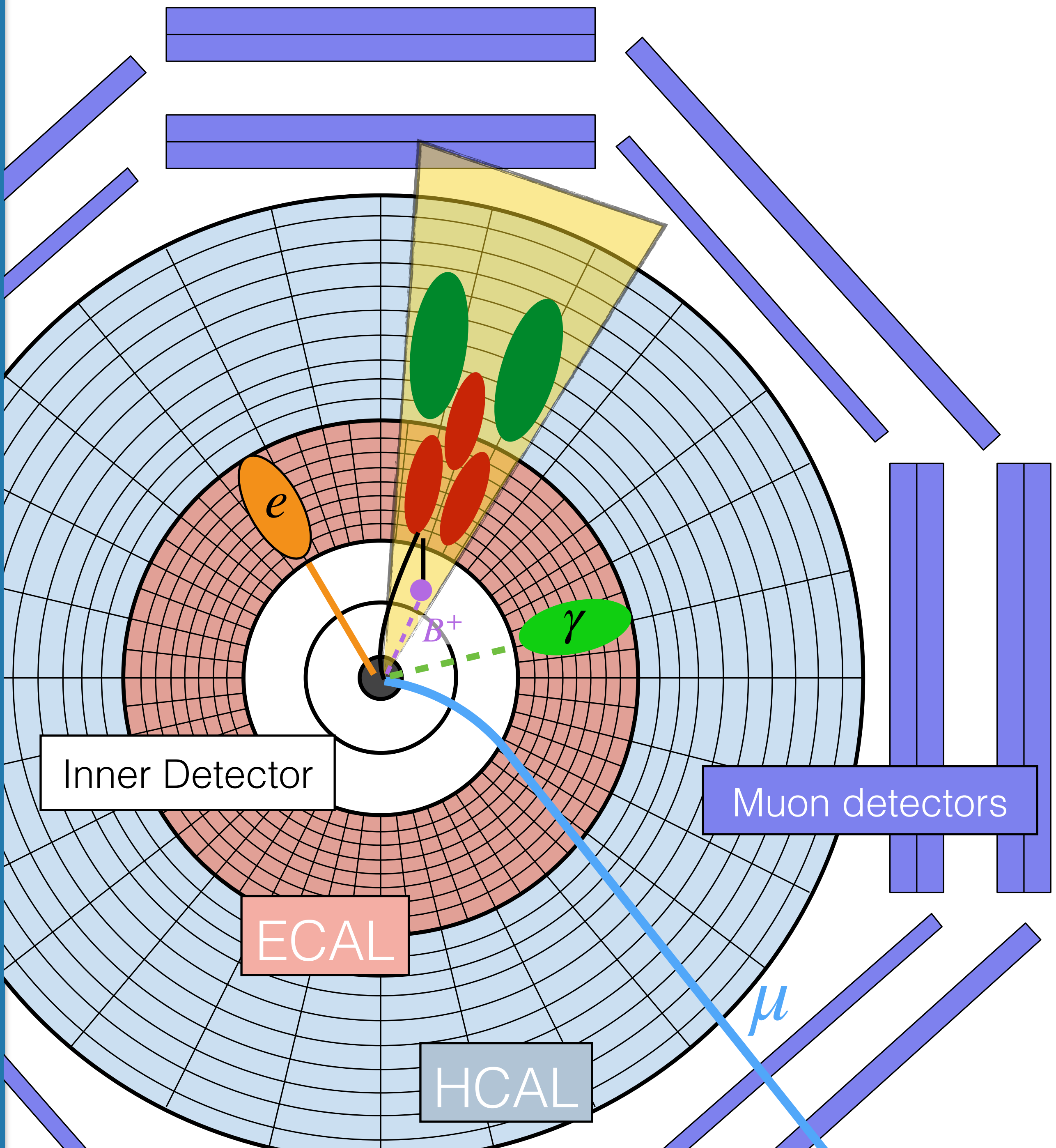

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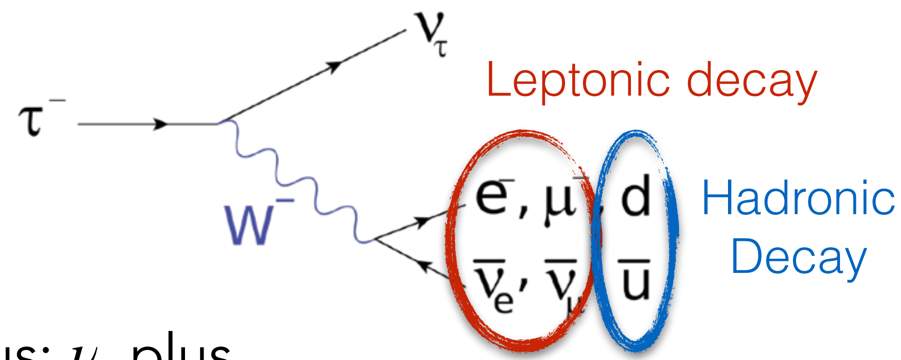

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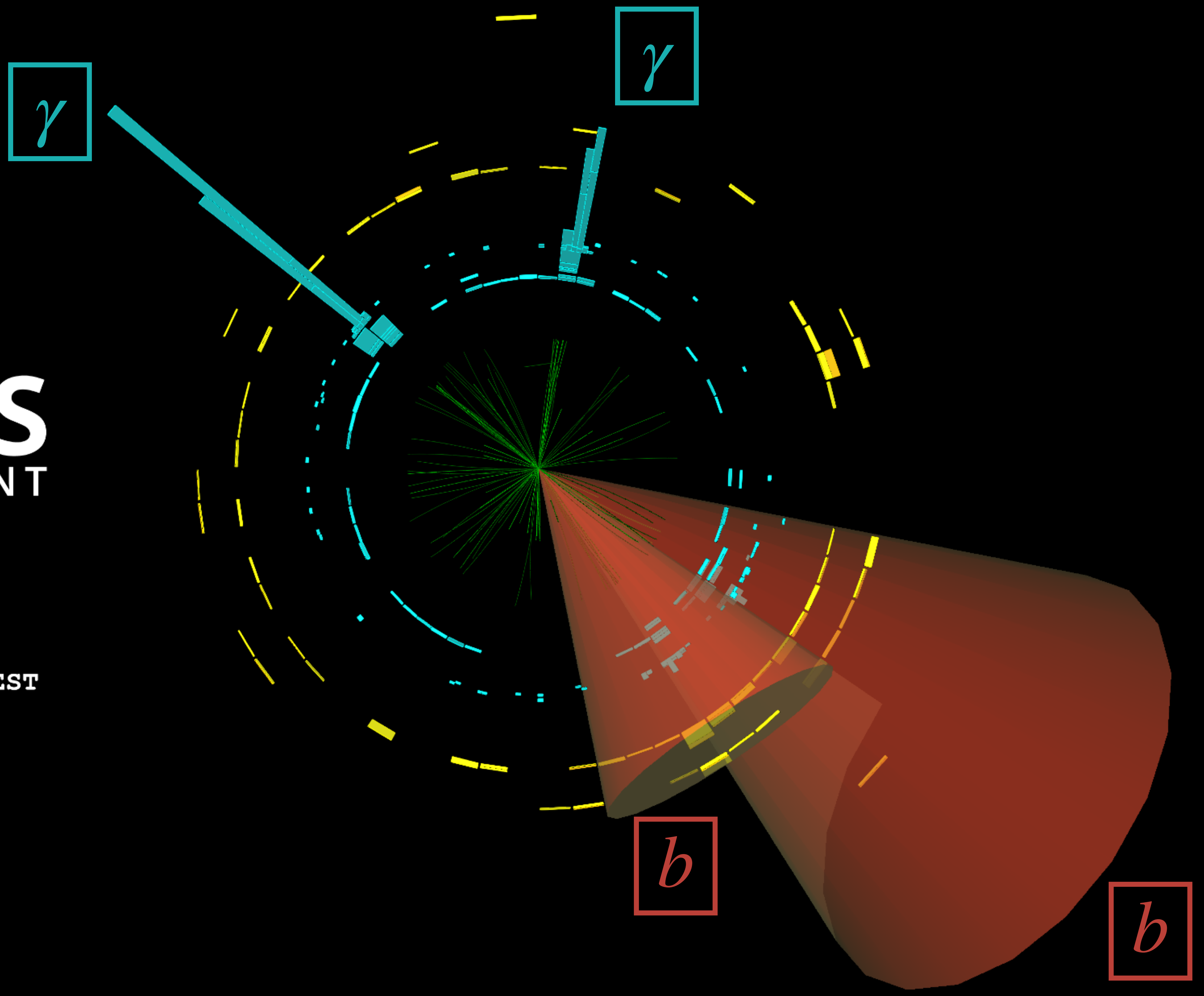
$HH \rightarrow b\bar{b}\gamma\gamma$ analysis ($139\ \mathrm{fb}^{-1}$)

JHEP 01 (2024) 066



Run: 329964
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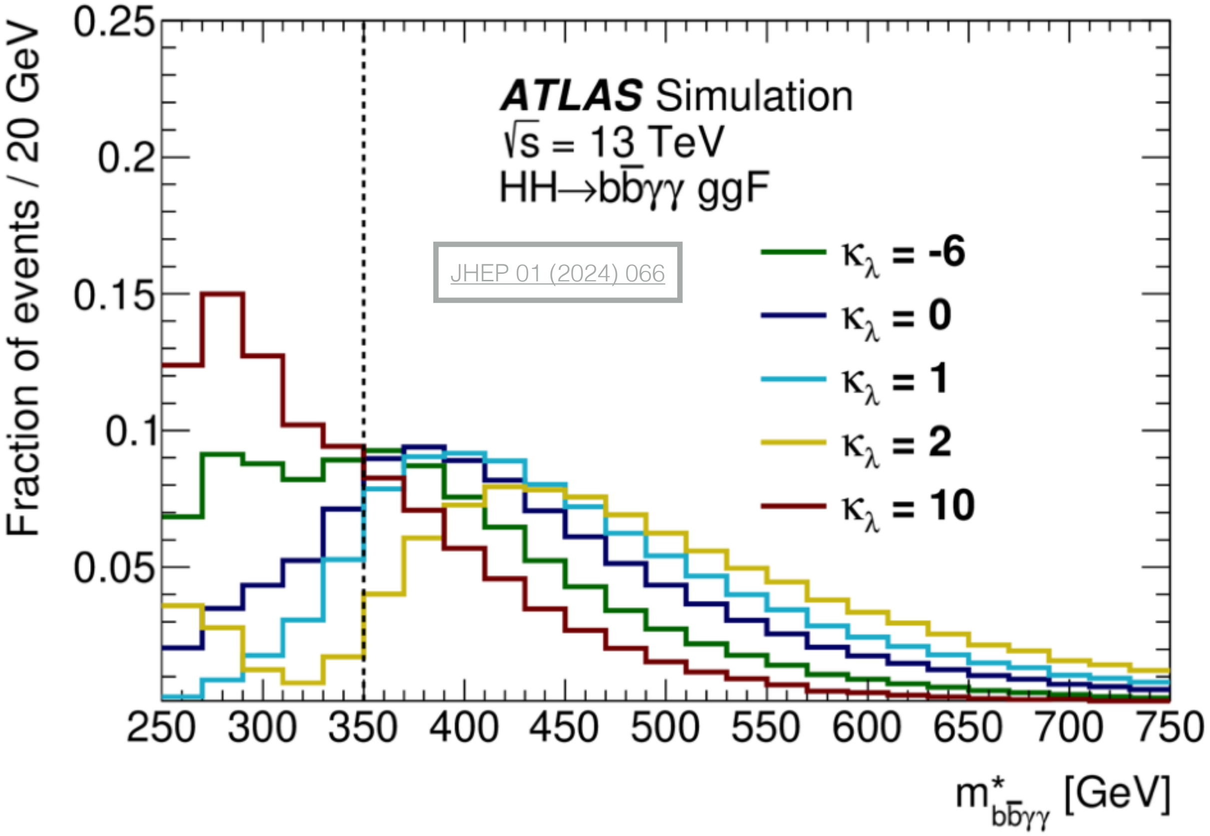
$HH \rightarrow b\bar{b}\gamma\gamma$ analysis (1)

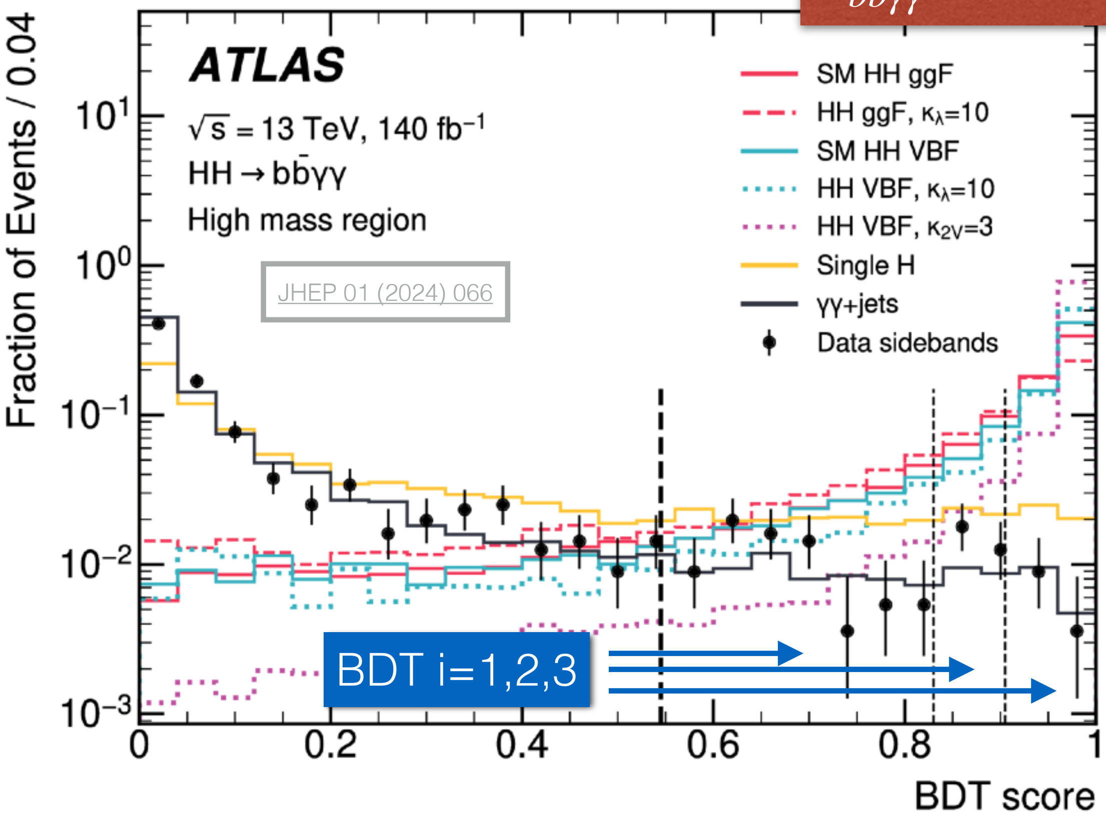
Analysis selection and categories

- **Very tiny HH BR** (0.26%), but **excellent acceptance** ($\gamma\gamma$ triggers) and **low backgrounds.**
- Selection: **2 photons** + **2 b-jets** (77% eff.)
  - **BDTs used** to separate backgrounds and signals.
- Categories: **7 regions** split in $m^*_{b\bar{b}\gamma\gamma}$ (350 GeV) and BDT output to enhance sensitivity to signal.

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\text{ GeV}$$



$m^*_{b\bar{b}\gamma\gamma}$ > 350 GeV

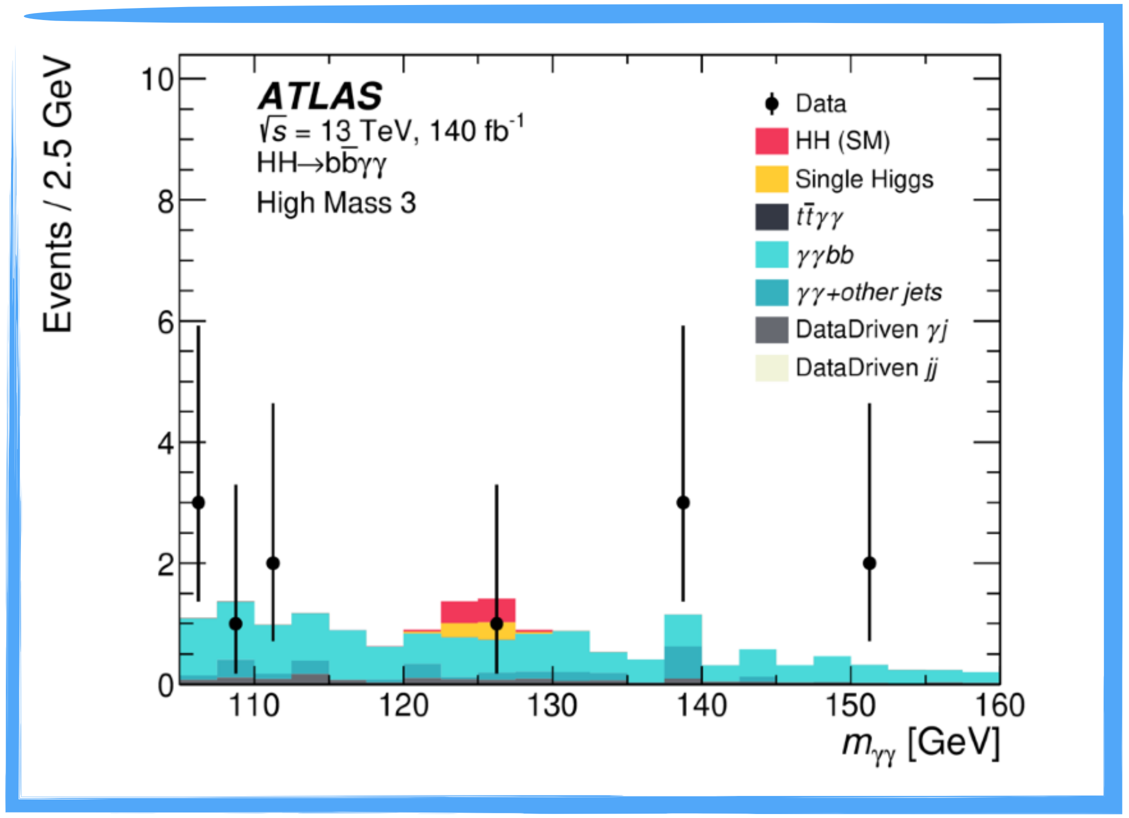


$HH \to b\bar{b}\gamma\gamma$ analysis (2)

Background estimation and results

Final observation: **simultaneous likelihood fit of $m_{\gamma\gamma}$** in 7 categories.

- Main backgrounds: $\gamma\gamma +$ **jets** and **SM** $H \to \gamma\gamma$.



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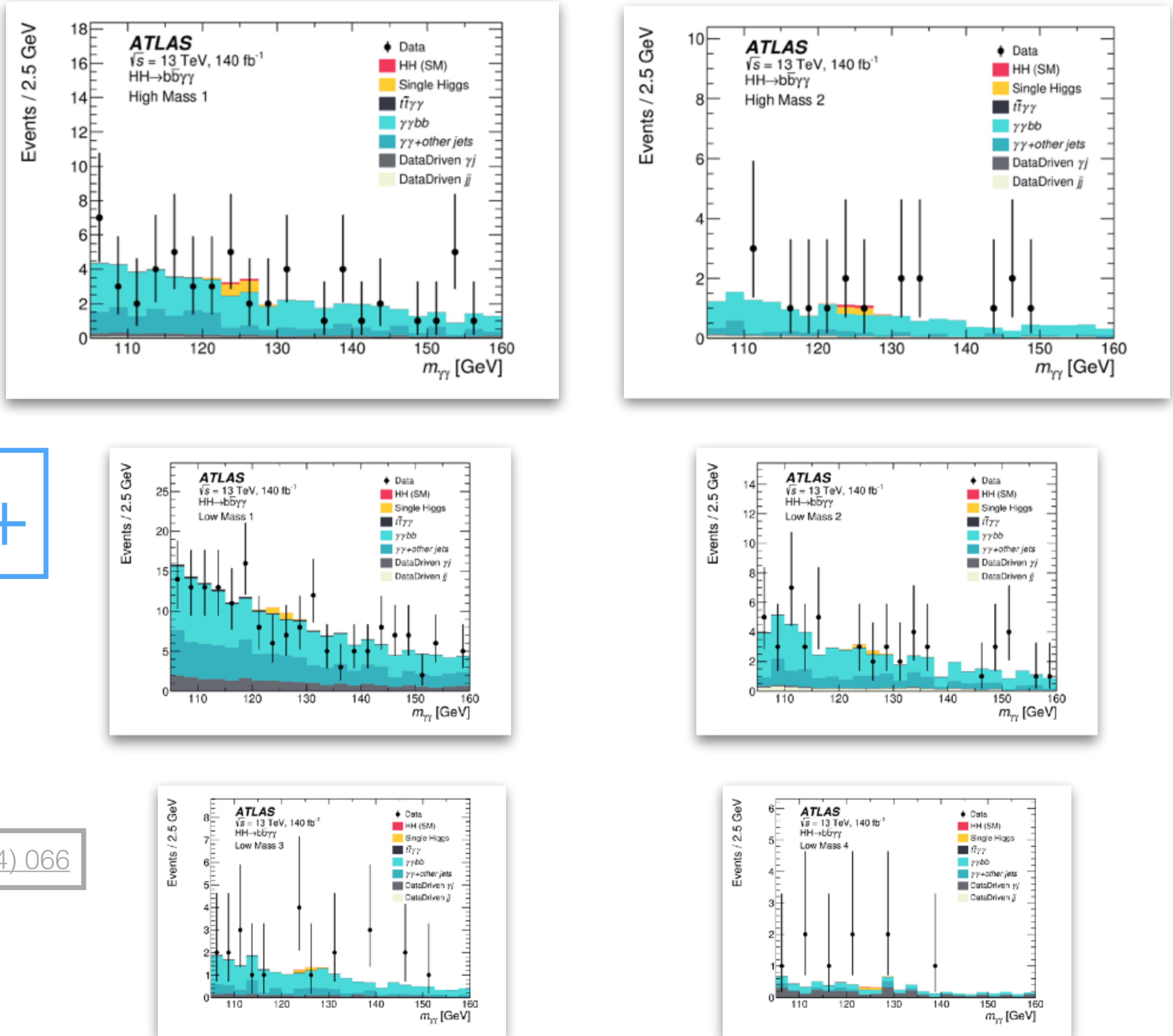
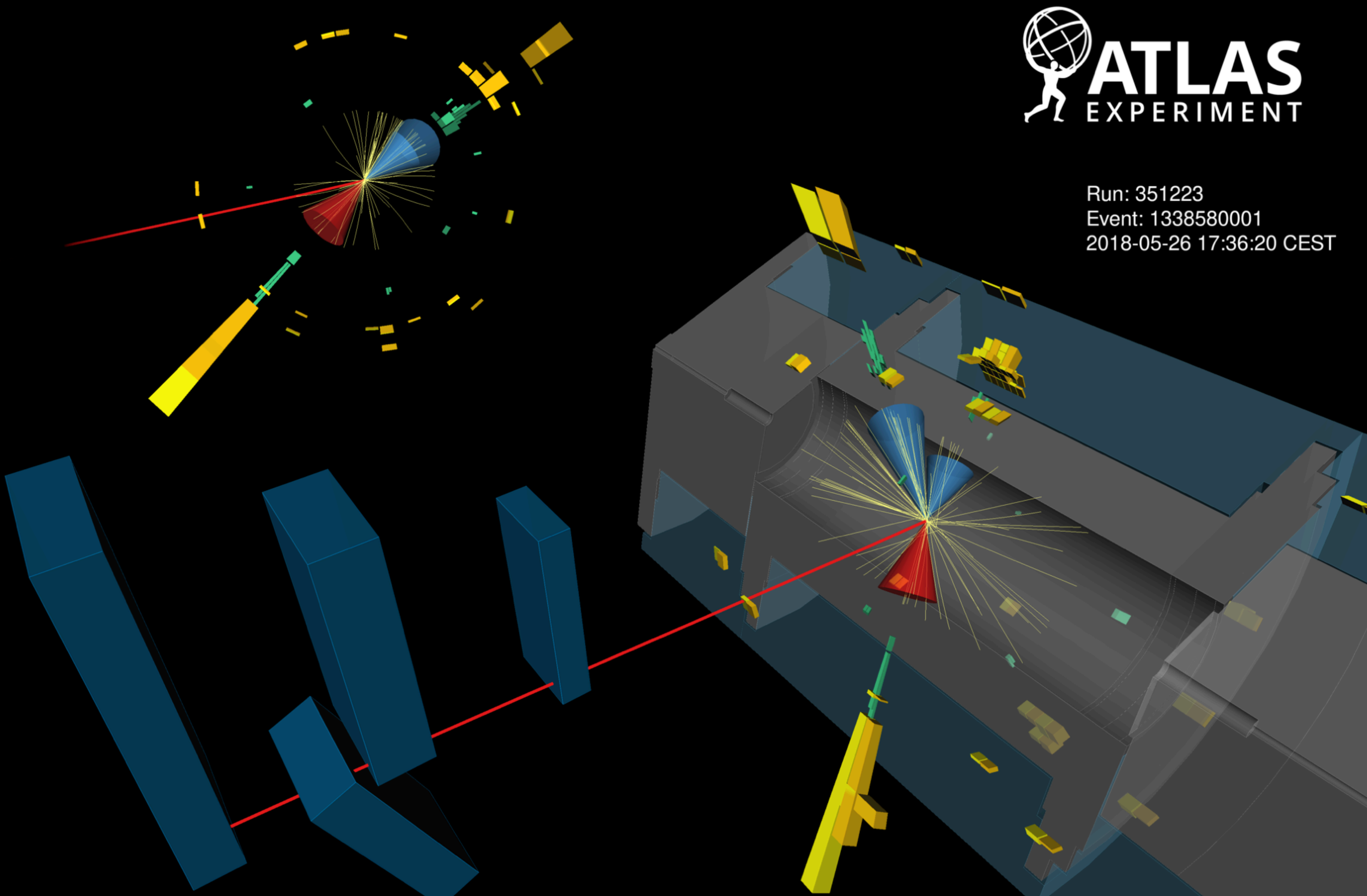


JHEP 01 (2024) 066

- **No significant excess** above SM prediction.

$HH \rightarrow b\bar{b}\tau^+\tau^-$ analysis (139 fb^{-1})

arXiv:2404.12660



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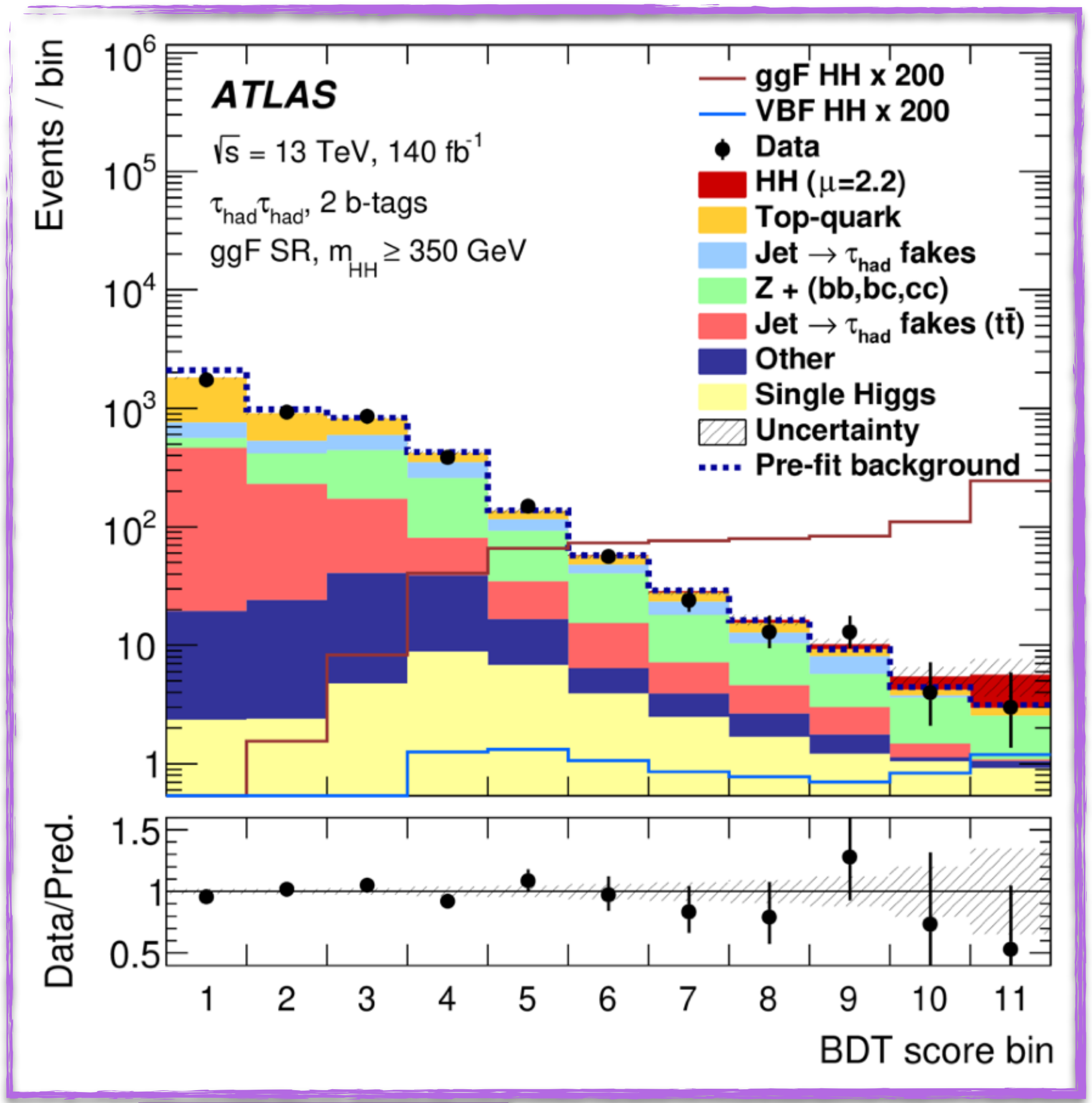
$HH \to b\bar{b}\tau\tau$ analysis (1)

Event selection and analysis categories

- **Good trade between HH BR** (7.3%) and **moderate background**.
- Selection: **2 b-jets** (77% eff.) and 2 **τ-leptons** (τ_{had} and τ_{lep})
  - **9 categories:** split in τ decay mode (had-had, lep-had) and HH production mode (ggF VBF) .
- **BDT outputs in categories are simultaneously fit** to separate background and signals.
- No significant excess observed.

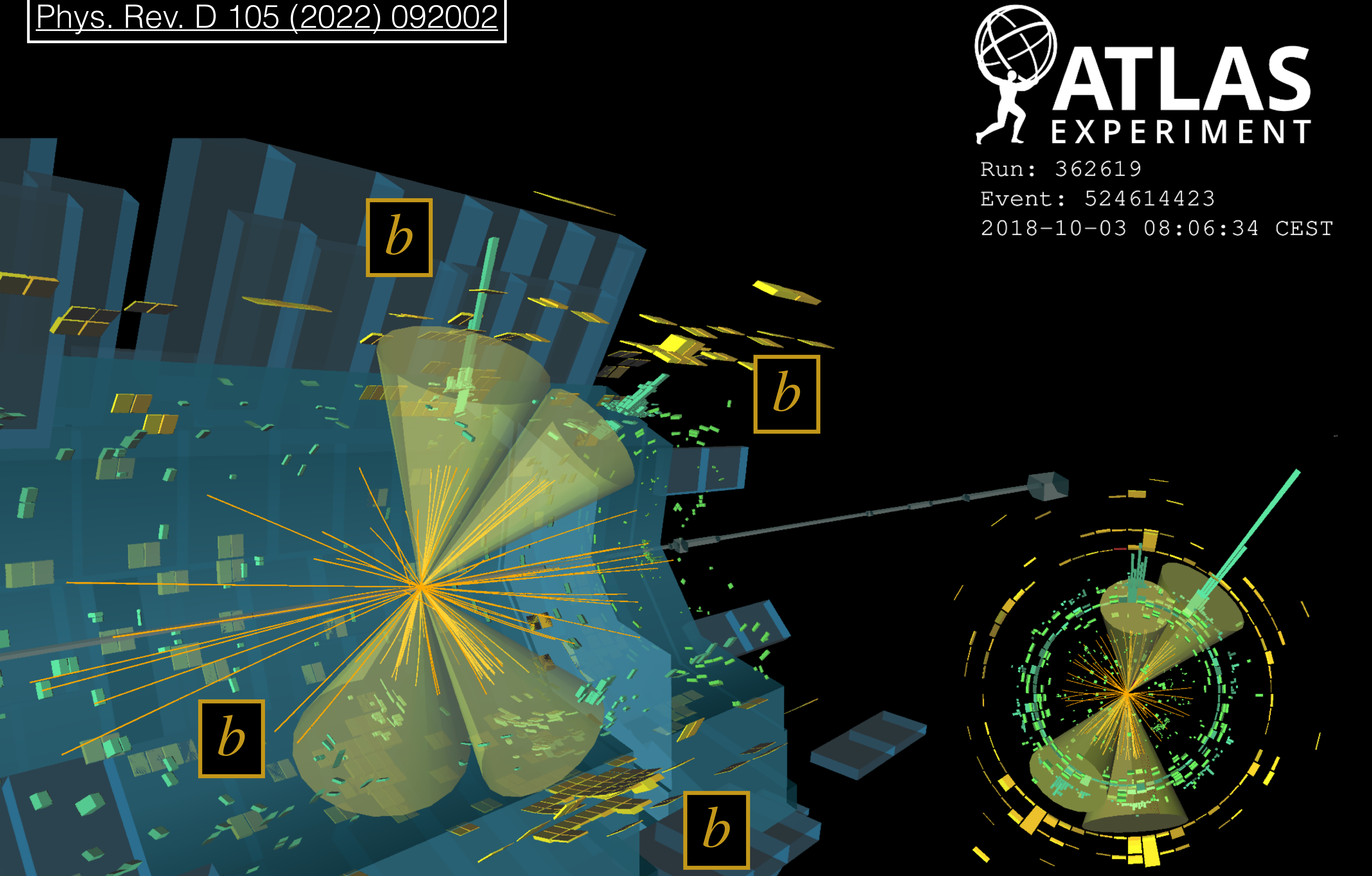
arXiv:2404.12660



+8 categories

$HH \to b\bar{b}b\bar{b}$ analysis (126 fb^{-1})

Phys. Rev. D 105 (2022) 092002

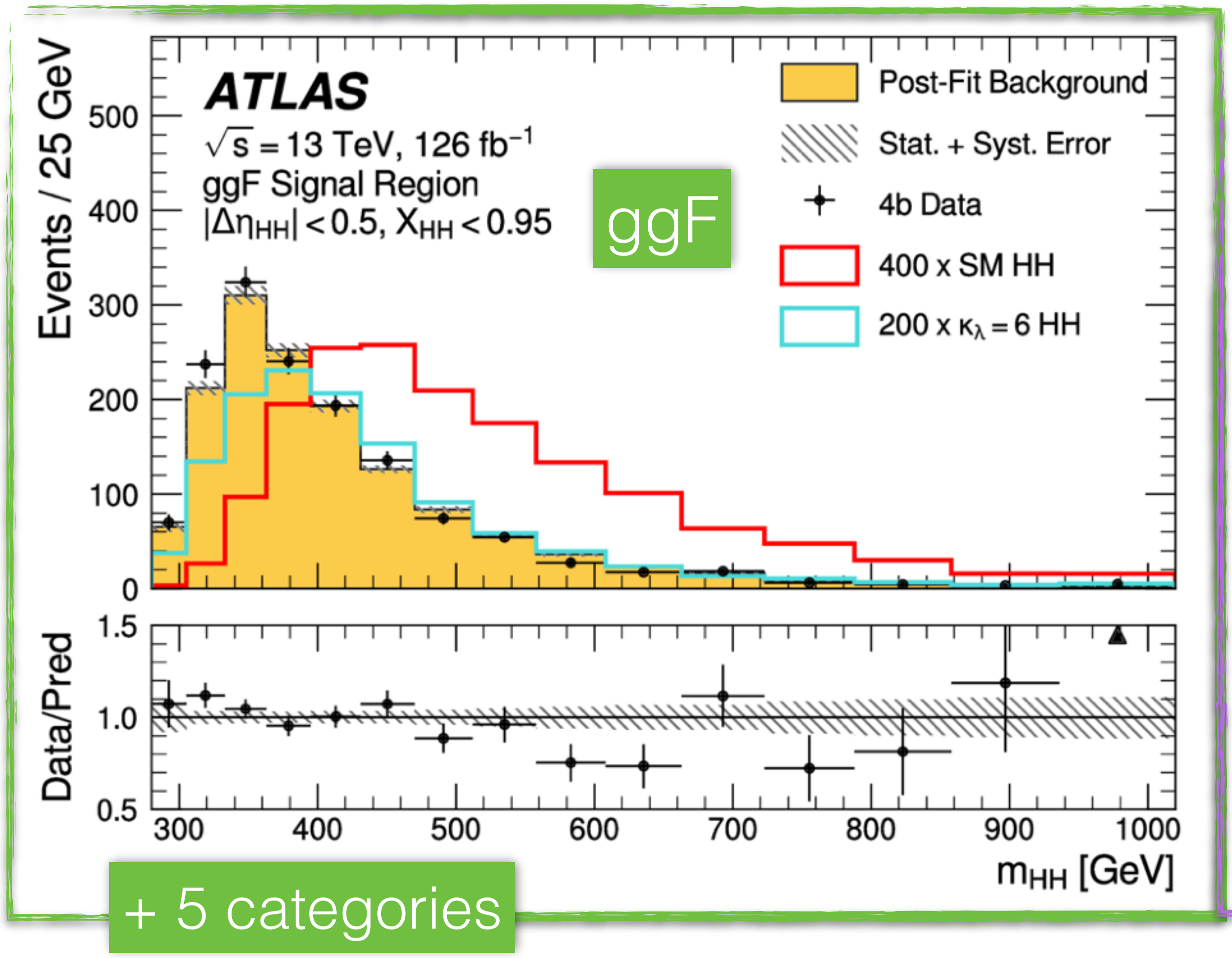


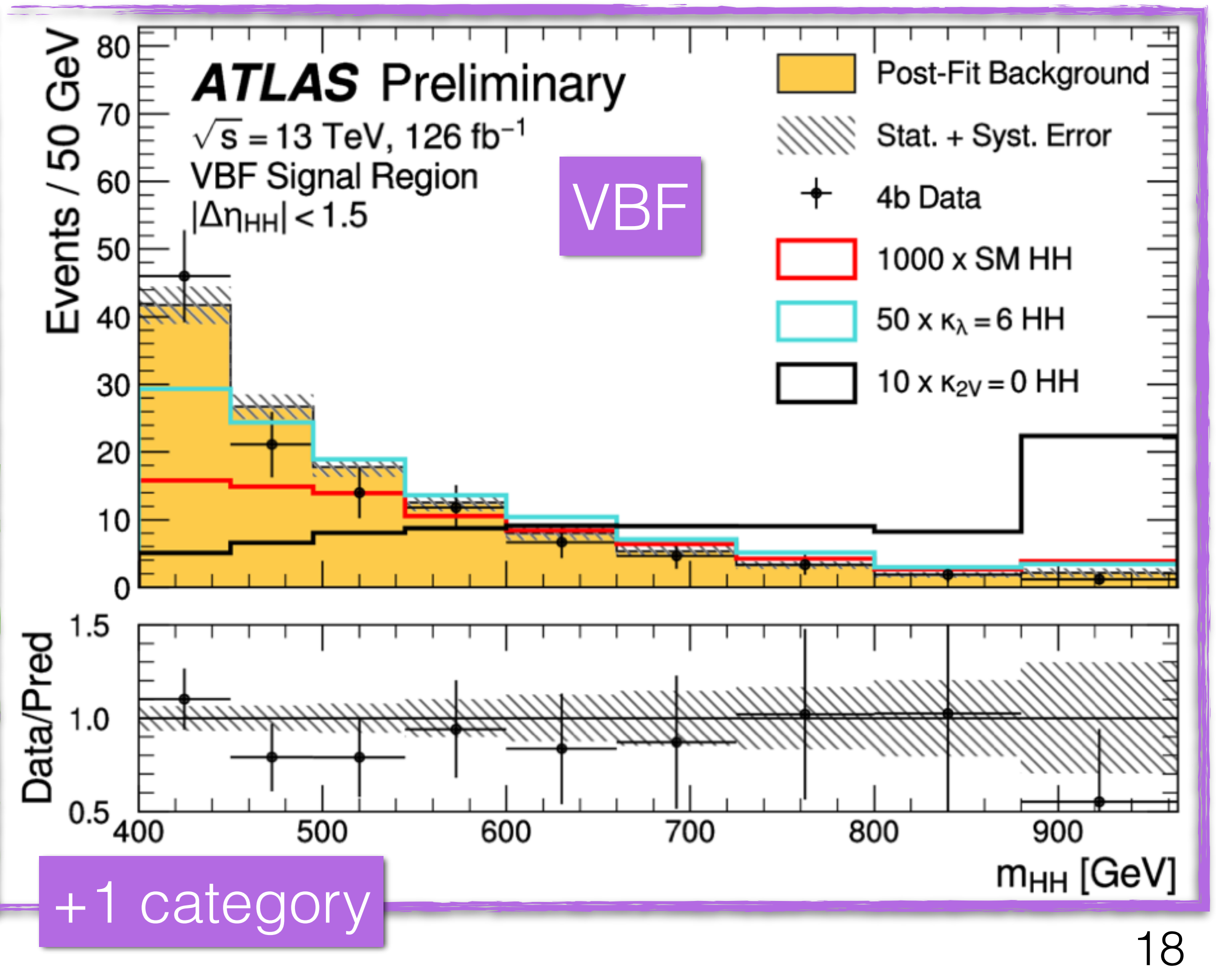
$HH \rightarrow b\bar{b}b\bar{b}$ analysis (1)

Selection and analysis categories

- **Largest HH BR** (34%), but **large multi-jet background** and challenging jet-pairing combinatorics.
- Selection: at least **4 b-jets** (77% eff.)
    - VBF selection: **two additional jets** close to the beam ($|\Delta\eta_{jj}| > 3$).
- Background estimation: fully data-driven with machine-learning-assisted ABCD method.
- Categories: **6 for ggF** and **2 for VBF** to enhance signal sensitivity.
- **No significant excess** observed.

Phys. Rev. D 105 (2022) 092002



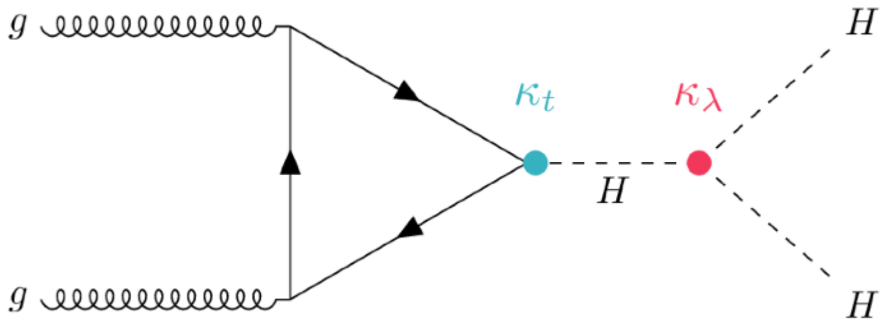


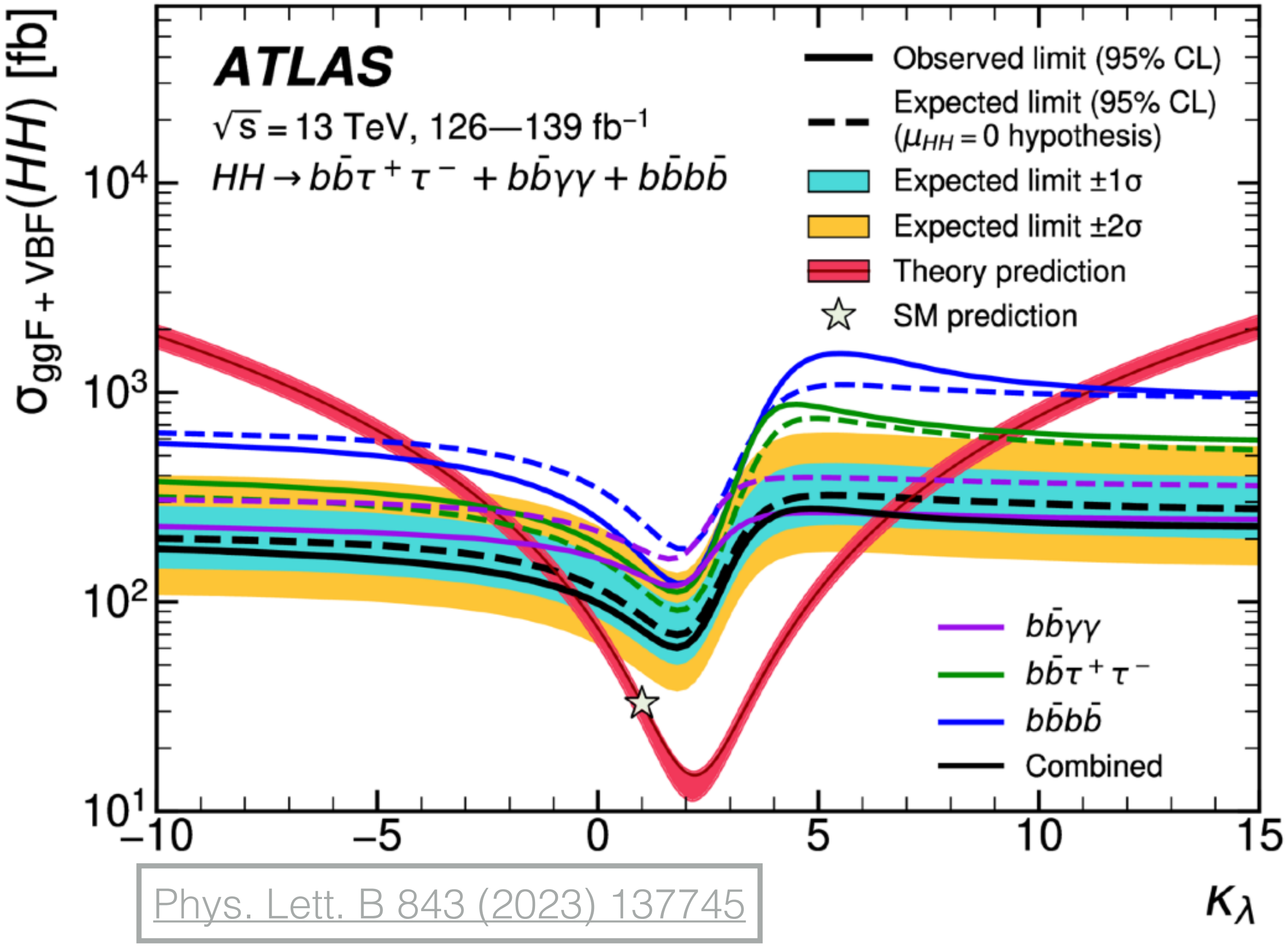
Combining everything together…

Higgs self-coupling constraints

Allowed κ_λ ranges

- **What did we learn** about the Higgs self-coupling?
- κ_λ **scan:** upper-limits on σ_{HH} assuming signal normalisation and kinematic at each value of κ_λ



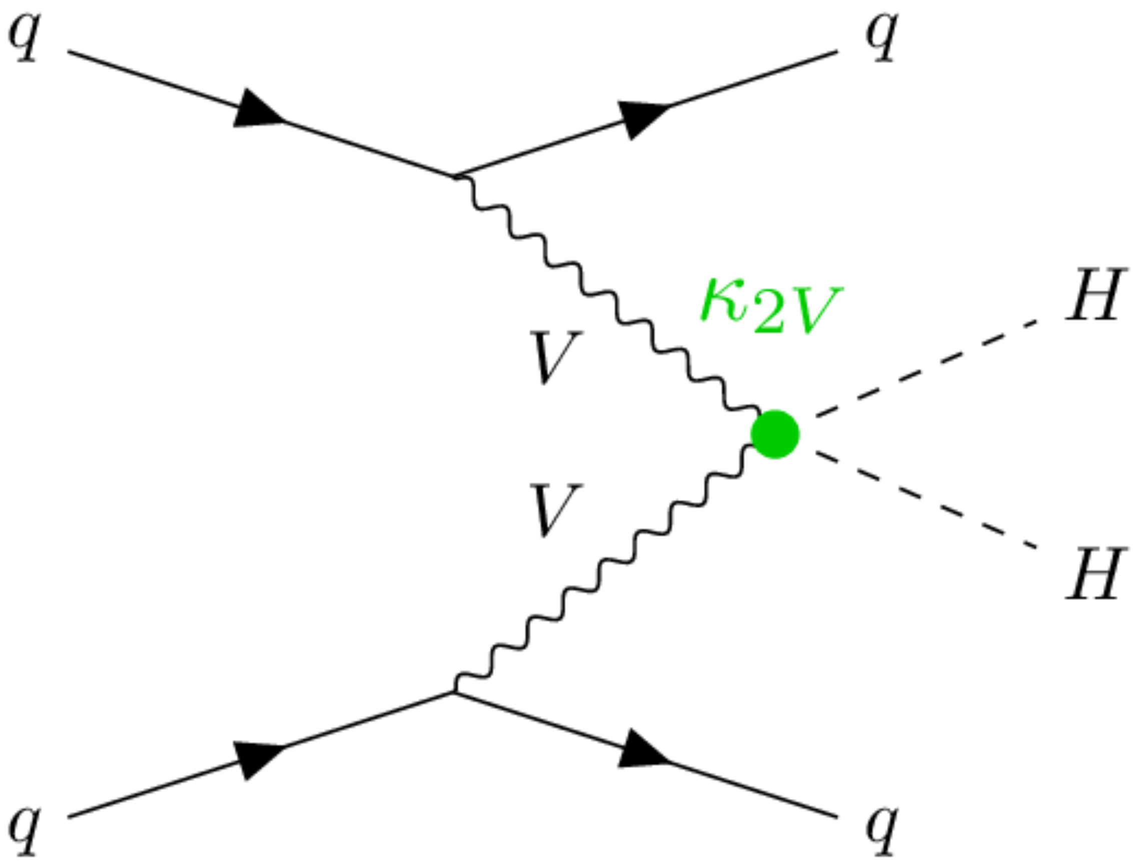


Phys. Lett. B 843 (2023) 137745

- Observed allowed κ_λ range is measured to be $-0.6 < \kappa_\lambda < 6.6$
- For the standard model point, combined observed (expected) 95% CL upper limit: $\mu_{SM}^{95\%} = 2.4\ (2.9)$!

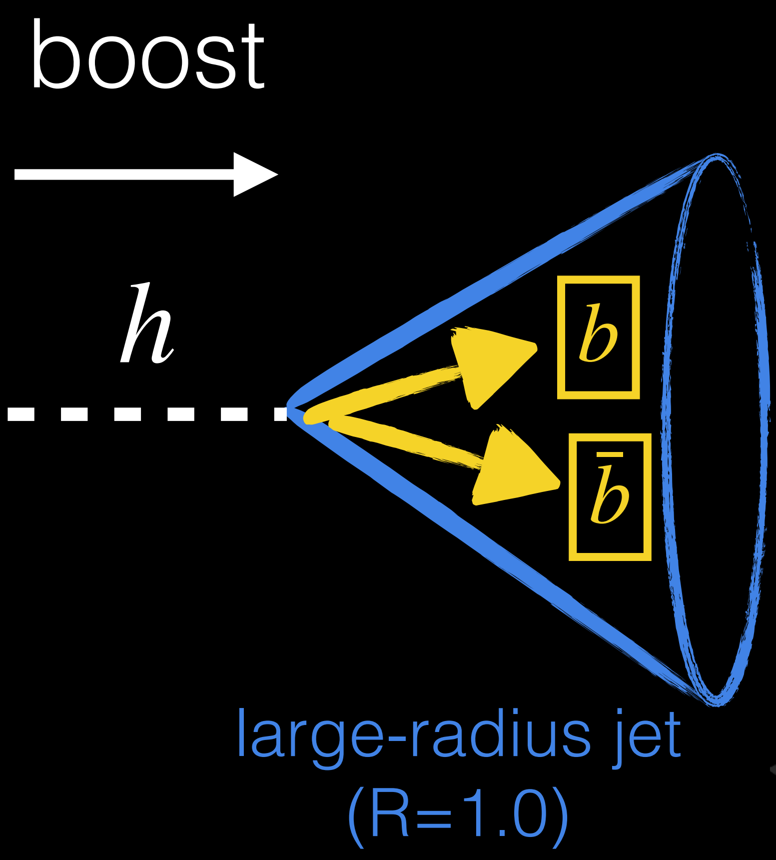
Very close to the SM signal! We are getting close to regions with exciting BSM physics scenarios!

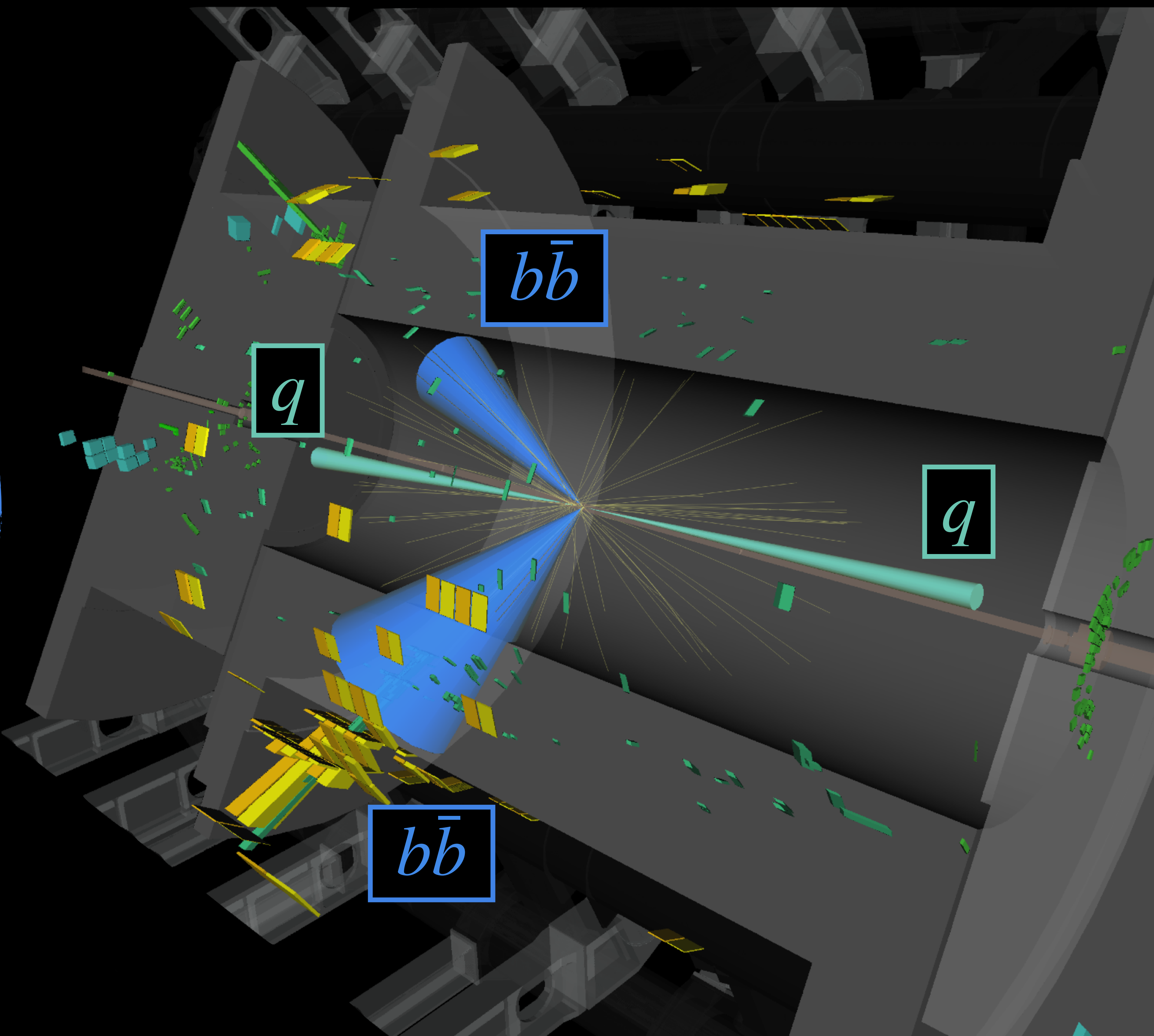
And for VBF (k_{2V})?



Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$ analysis ($139\ \mathrm{fb}^{-1}$)

arXiv:2404.17193





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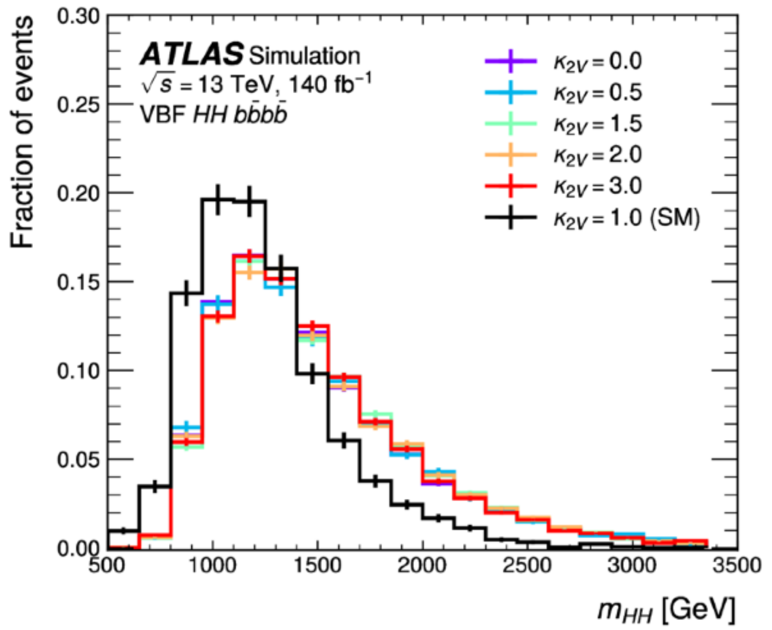
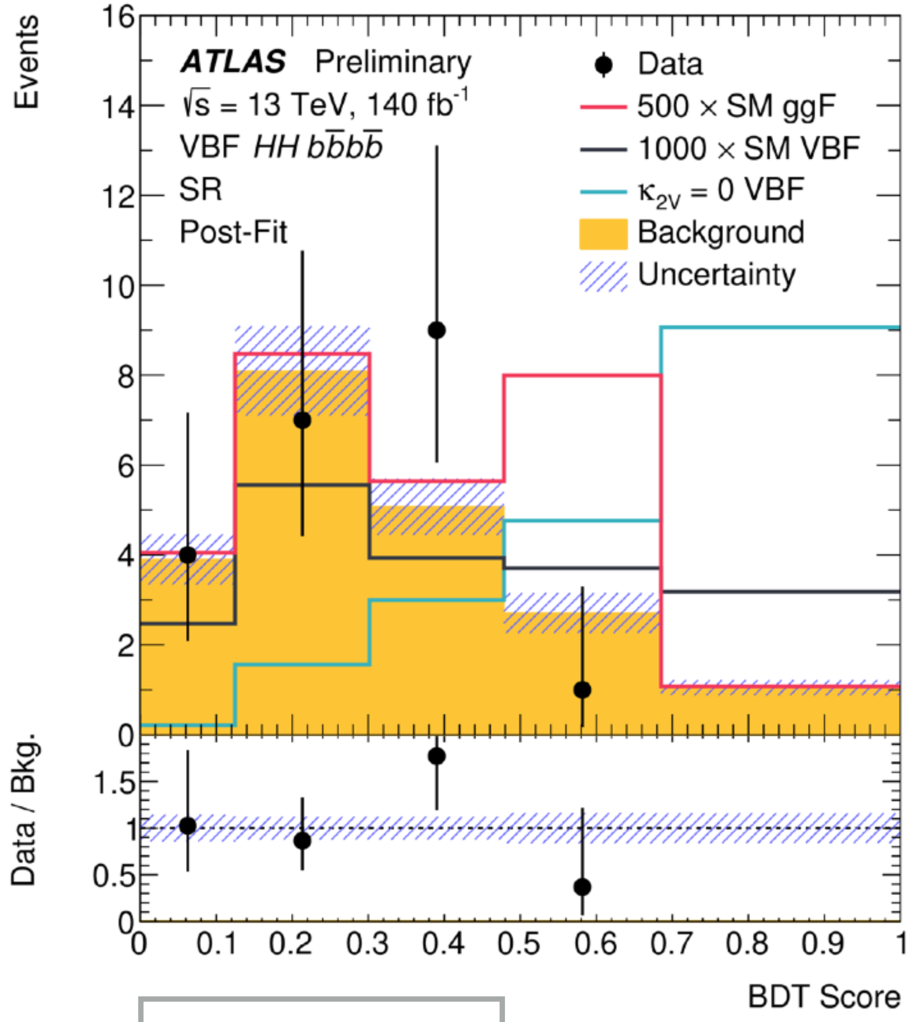
Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$

Analysis strategy

- Extremely **high sensitivity to k_{2V} variations** due to kinematic boost of Higgs bosons.
  - Less statistics, but also **much less backgrounds!**
- $H \rightarrow b\bar{b}$ identified through **dedicated machine-learning double-b tagger** (ATL-PHYS-PUB-2020-019).
- Selection:
  - **2 large-radius jets** tagged as $H \rightarrow b\bar{b}$ (60% eff.)
  - **2 small-radius jets** close to the beam ($|\Delta\eta(j,j)| > 3$)
- Background estimation: fully data-driven ABCD method.
- No excess above SM prediction.





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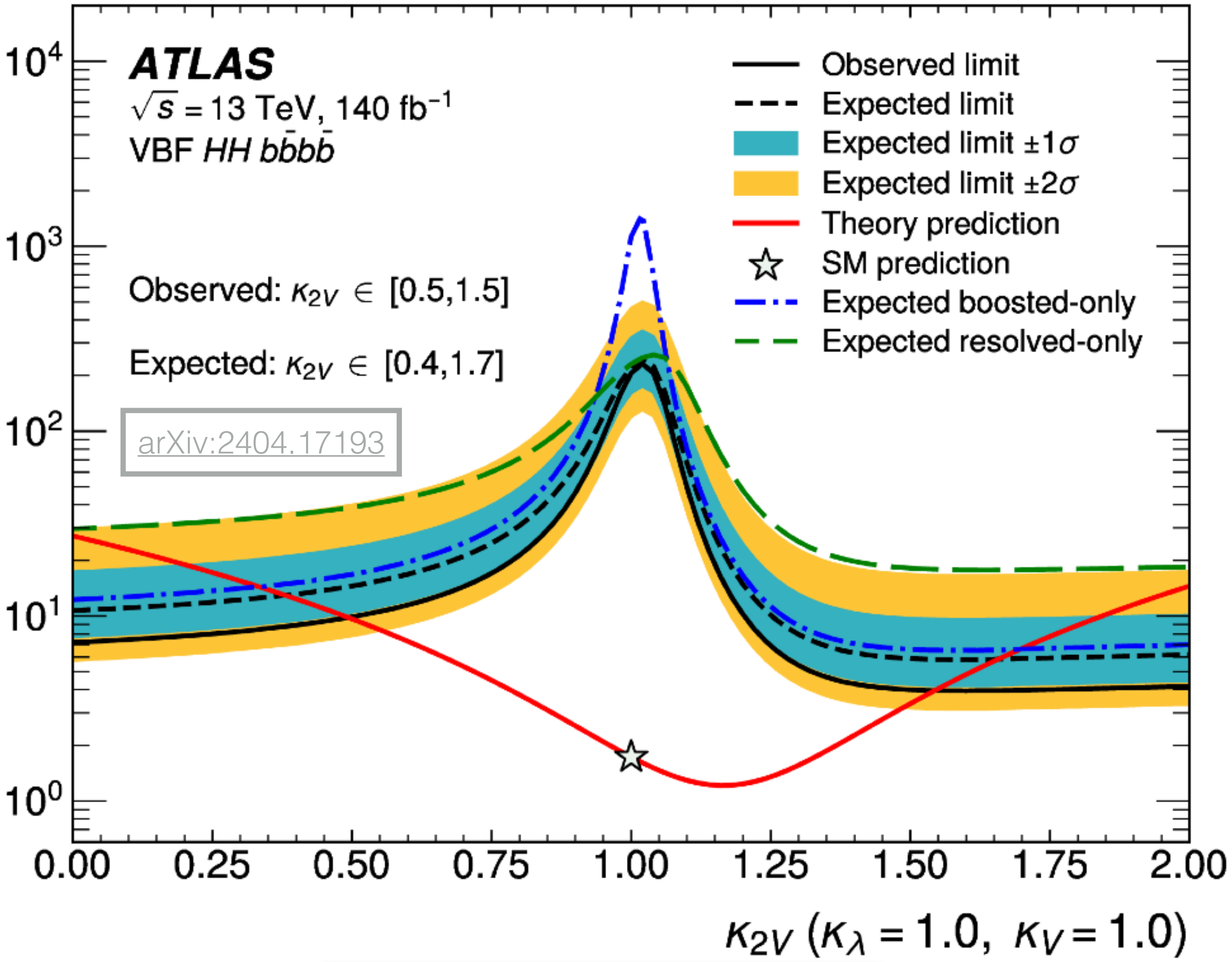
Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$

k2V limits

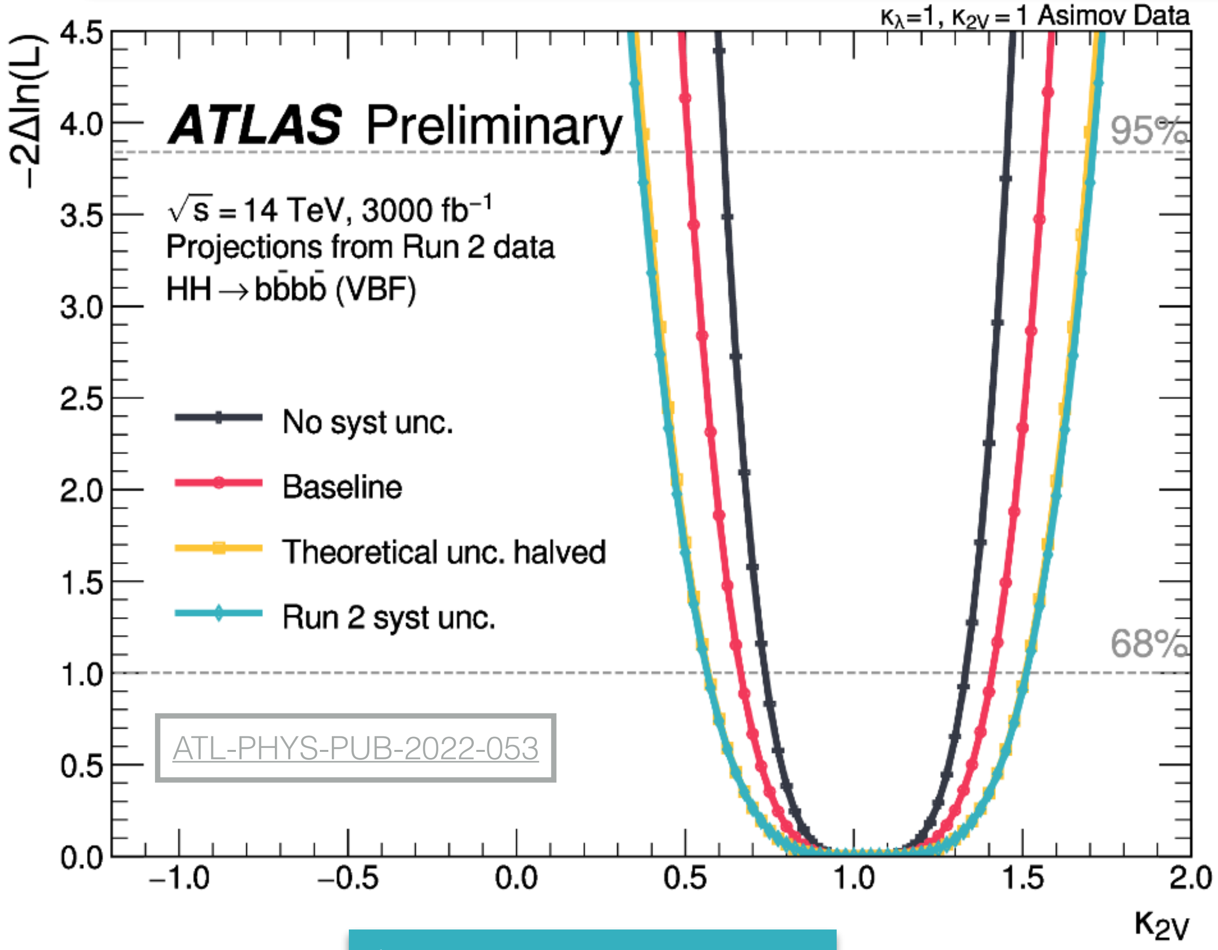
- At 95% CL: $\kappa_{2V} \in [0.52, 1.52]$ (boosted-only)!
    - Much more sensitive than resolved $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ ($\kappa_{2V} \in [0.1, 2.0]$)!
- Even more **sensitive than expected sensitivity at the HL-LHC (3000 fb^{-1})! A huge step forward in just a couple of years!**

Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$ (140 fb^{-1})



$k_{2V} \in [0.52, 1.52]$

Resolved $HH \rightarrow b\bar{b}b\bar{b}$ at HL-LHC (3000 fb^{-1})



$k_{2V} \in [0.4, 1.7]$

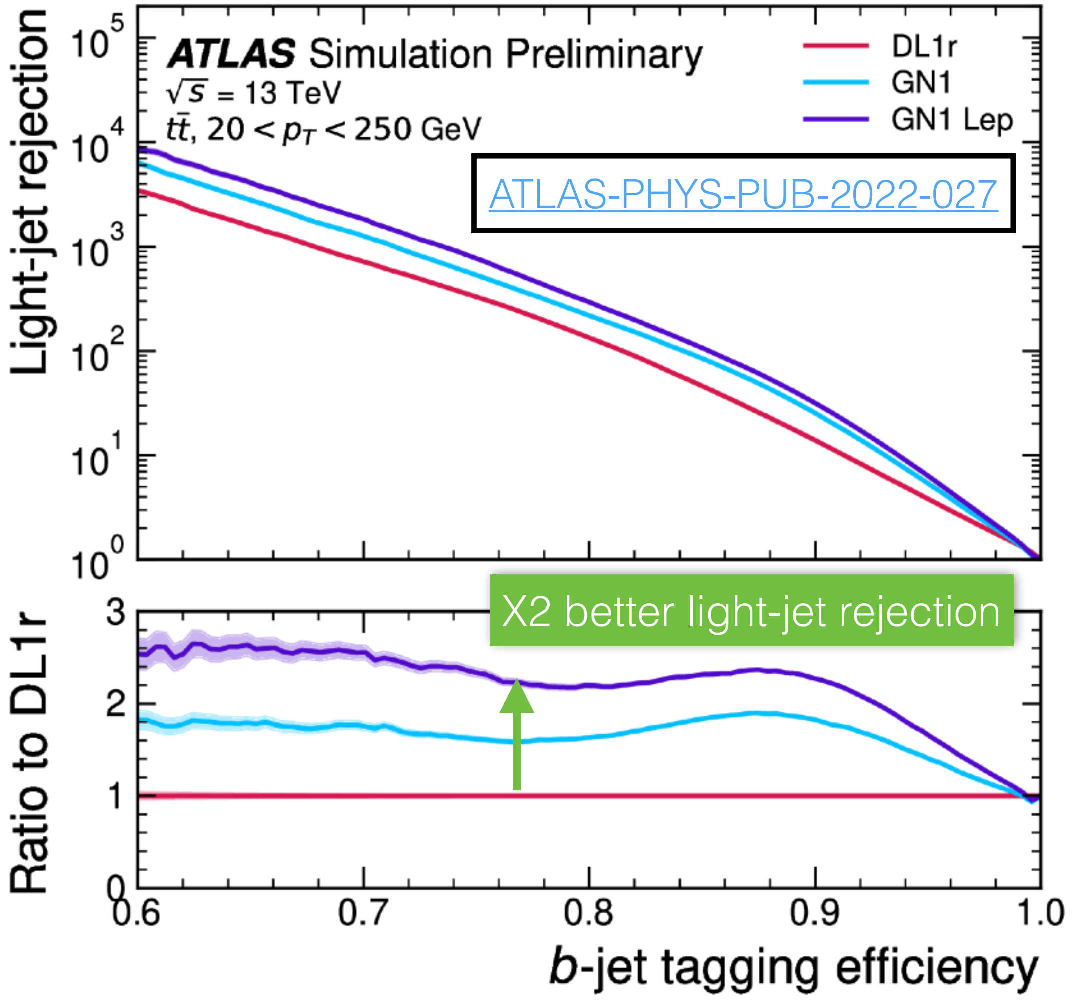
So no unexpected Higgs self-coupling values for now.

Can we improve the precision in future?

Run 3 ATLAS improvements

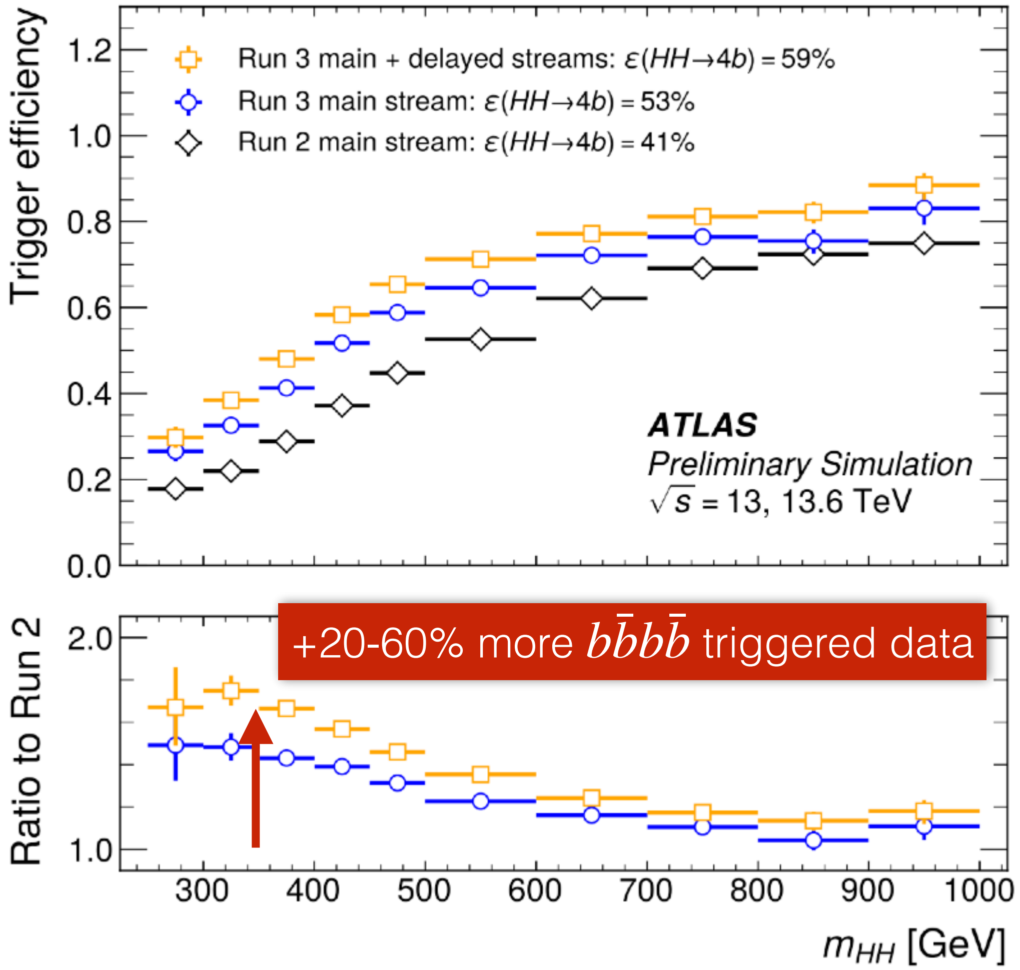
More data, better reconstruction and triggers

- Expect a **large number of improvements** by the end of Run 3 (2022-2025).
  - **More data** ($150 - 250$ fb^{-1}in Run 3) and +10% $\sigma(HH)$ with $\sqrt{s} = 13.6$ TeV
  - **b-tagging largely improved** with Graph Neural Networks!
  - **Triggers significantly improved** (e.g. asymmetric $HH \rightarrow b\bar{b}b\bar{b}$ triggers)!



ATLAS-PHYS-PUB-2022-027

X2 better light-jet rejection



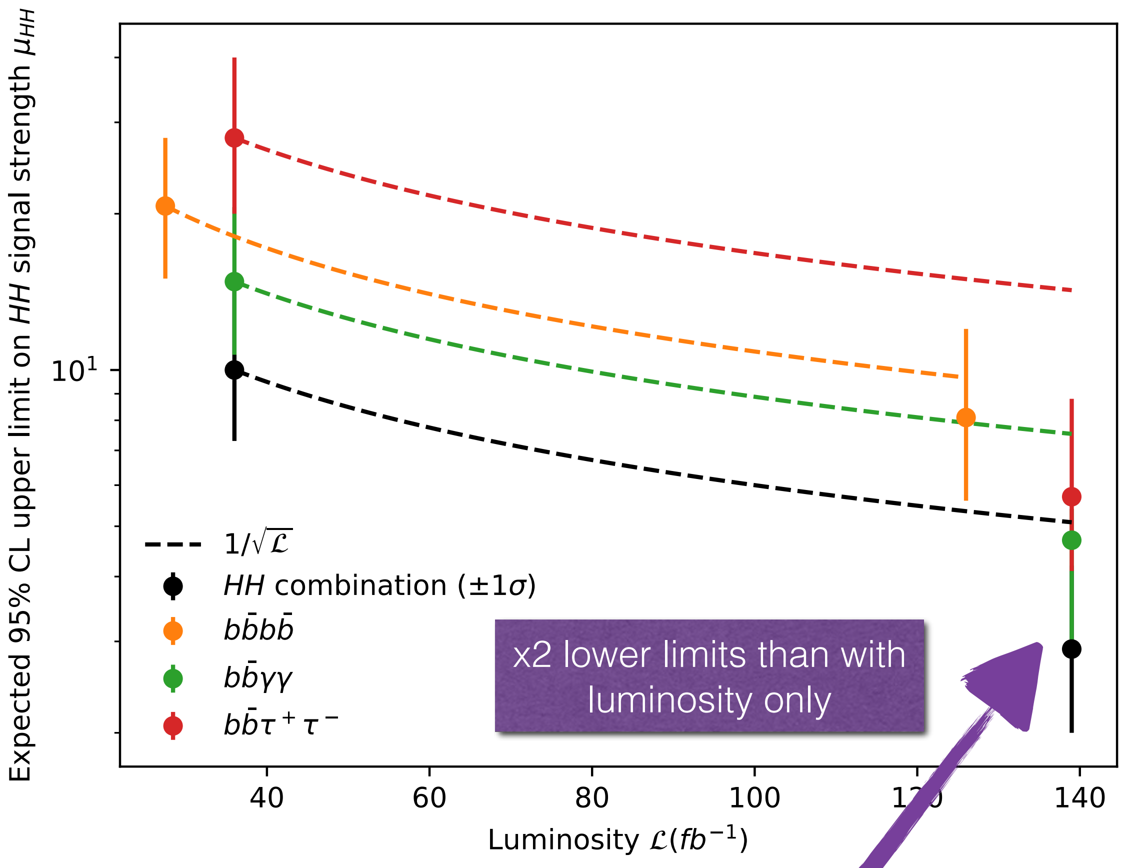
+20-60% more $b\bar{b}b\bar{b}$ triggered data

Conclusion and prospects

- The Higgs sector is **UNIQUE** and still **largely unexplored**!
  - Shape of the **Higgs potential essential** to fully understand EWSB and the evolution of the universe.

Only started to understand the Higgs!

- **HH searches** at the (HL-)LHC are currently the **best tool** to constrain $V(\phi)$:
  - **Huge improvements on κ_λ and κ_{2V} constraints achieved** with Run 2 ATLAS dataset.
  - 5σ discovery achievable at the HL-LHC (ATLAS+CMS).
  - **More improvements are expected for Run 3** (more data, better triggers, better physics object identification, etc.).



x2 lower limits than with luminosity only

The human factor is important!

If something is unexpected in the Higgs potential, Run 3 might already reveal this to us!

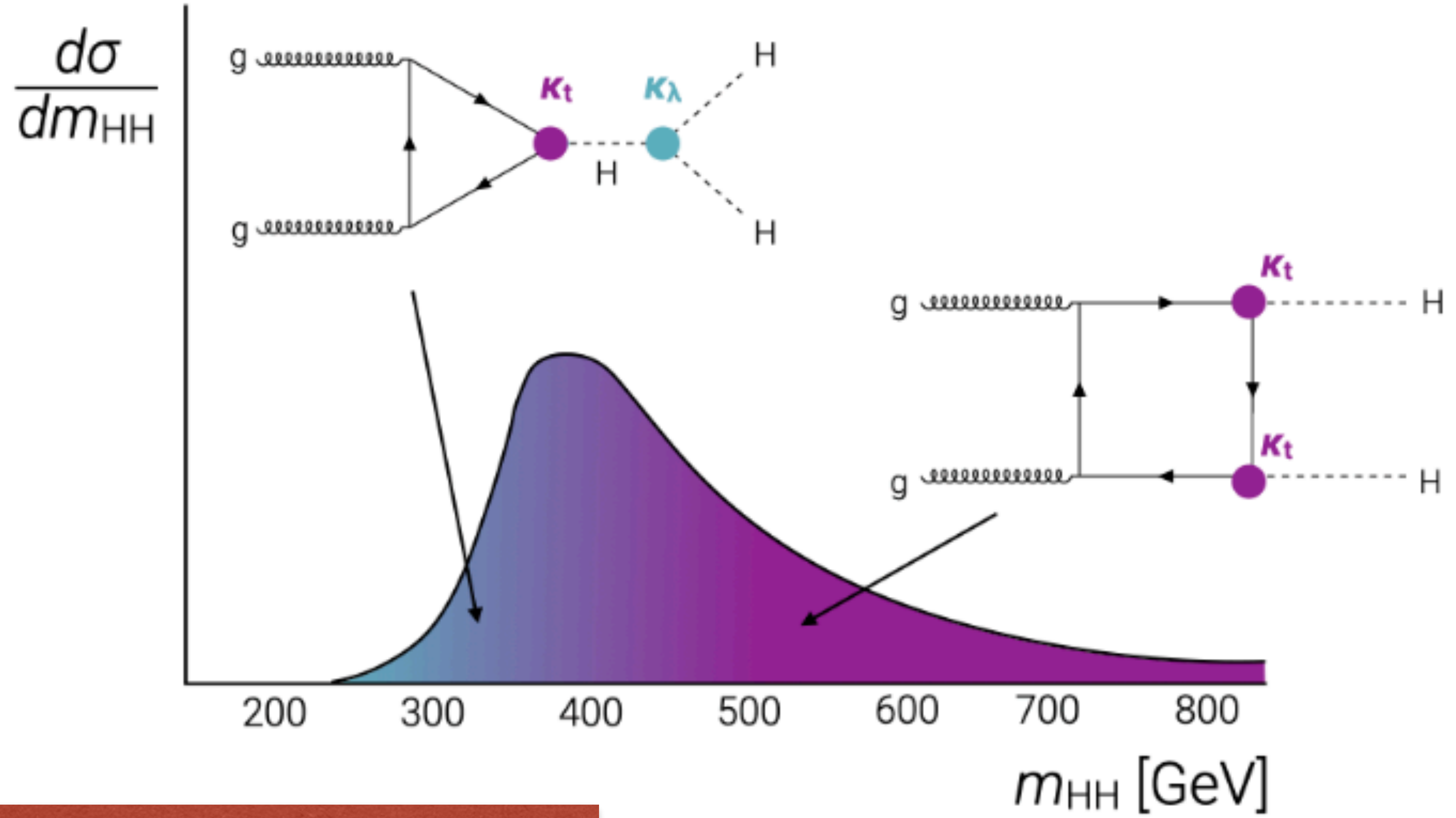
Thank you for your attention!

Backup

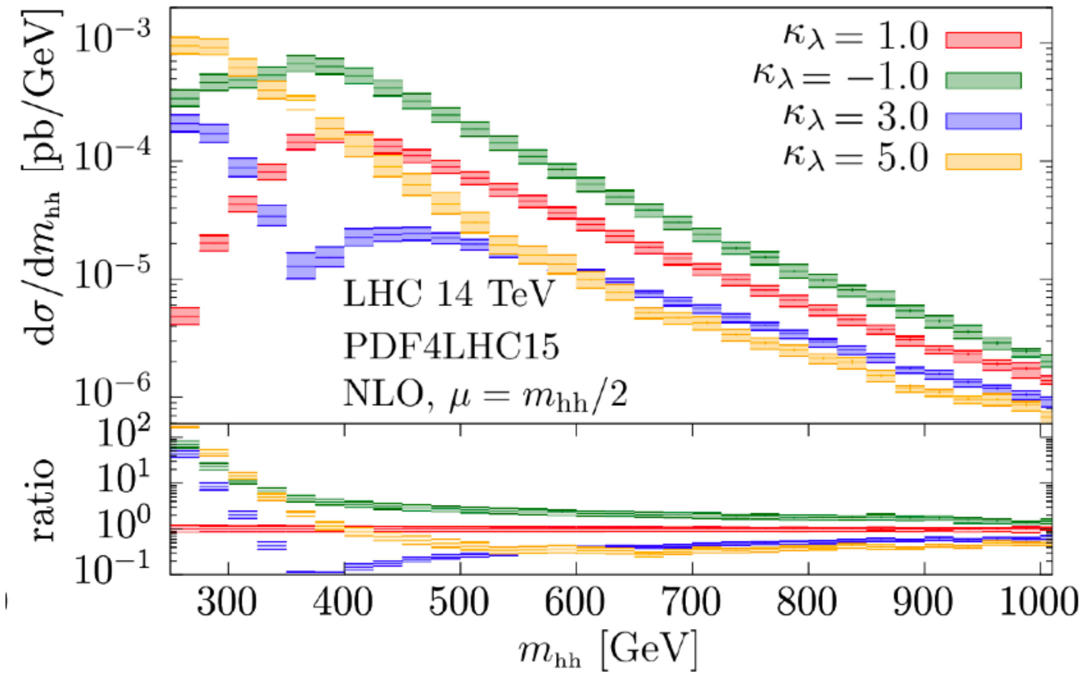
Challenges of HH production at the LHC

The unbearable lightness of HH

Not only small cross-section, **but also complex signal kinematic** due to diagram interference!



arXiv:1903.08137



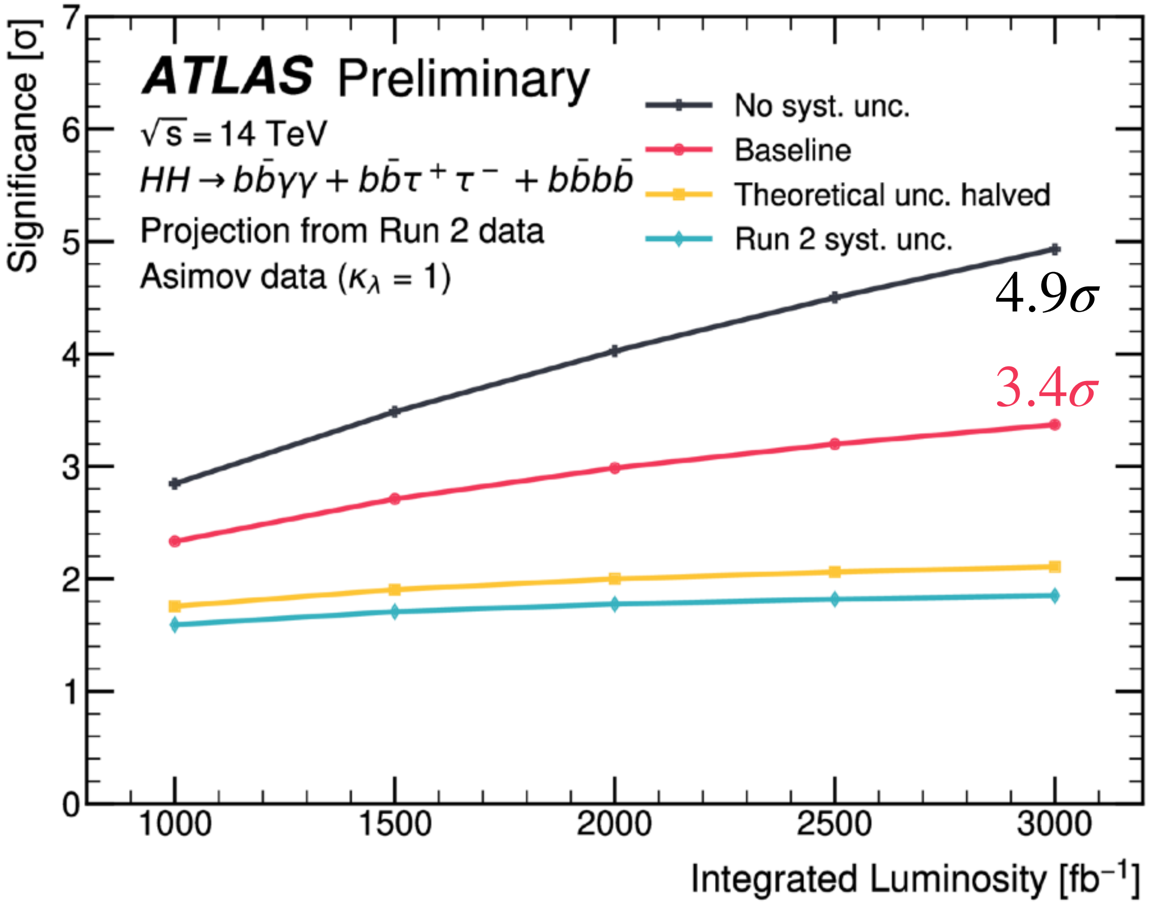
Impact of κ_λ more visible in soft part (i.e. low p_T) of the m_{HH} spectrum

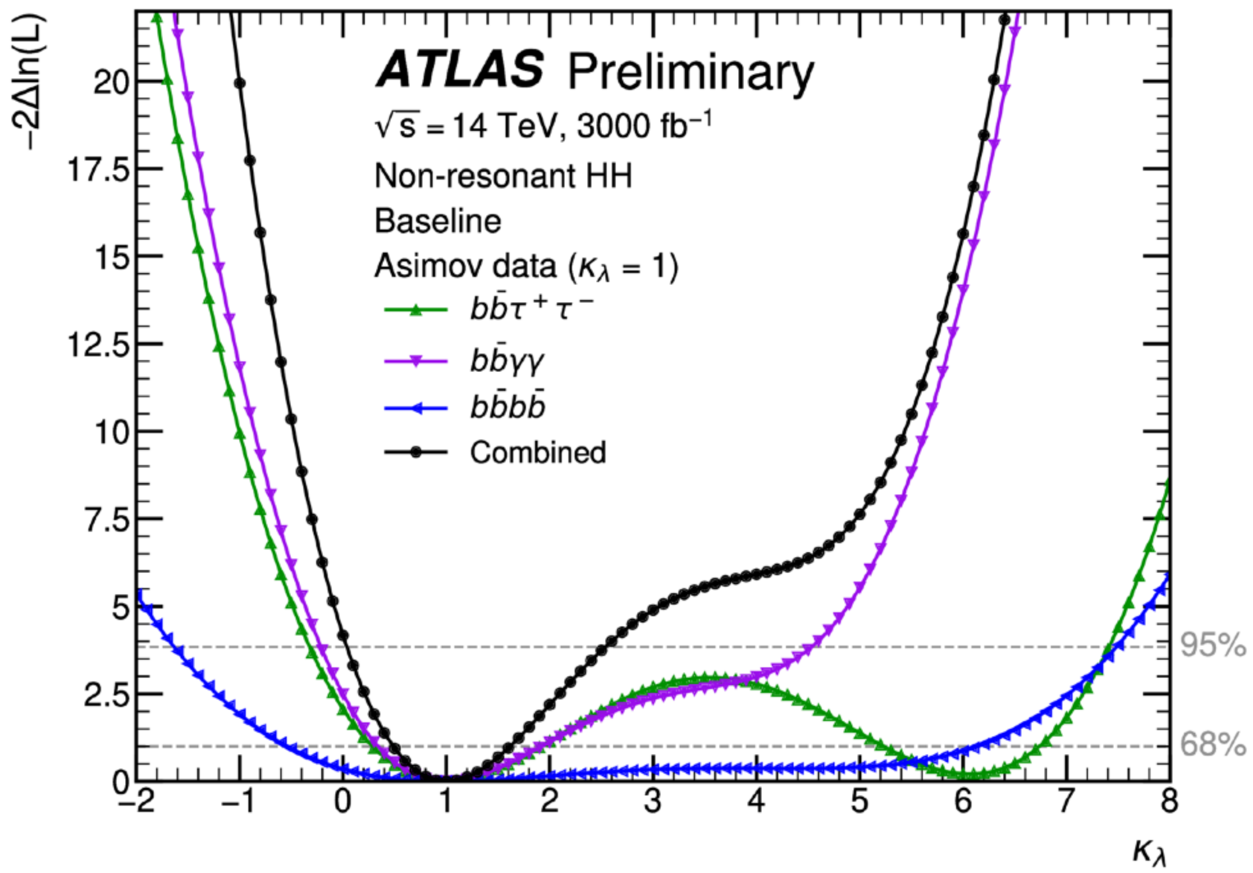
Access low m_{HH} events is hard due to soft Higgs kinematics!

Updated HL-LHC projections for HH

ATLAS-PHYS-PUB-2022-053

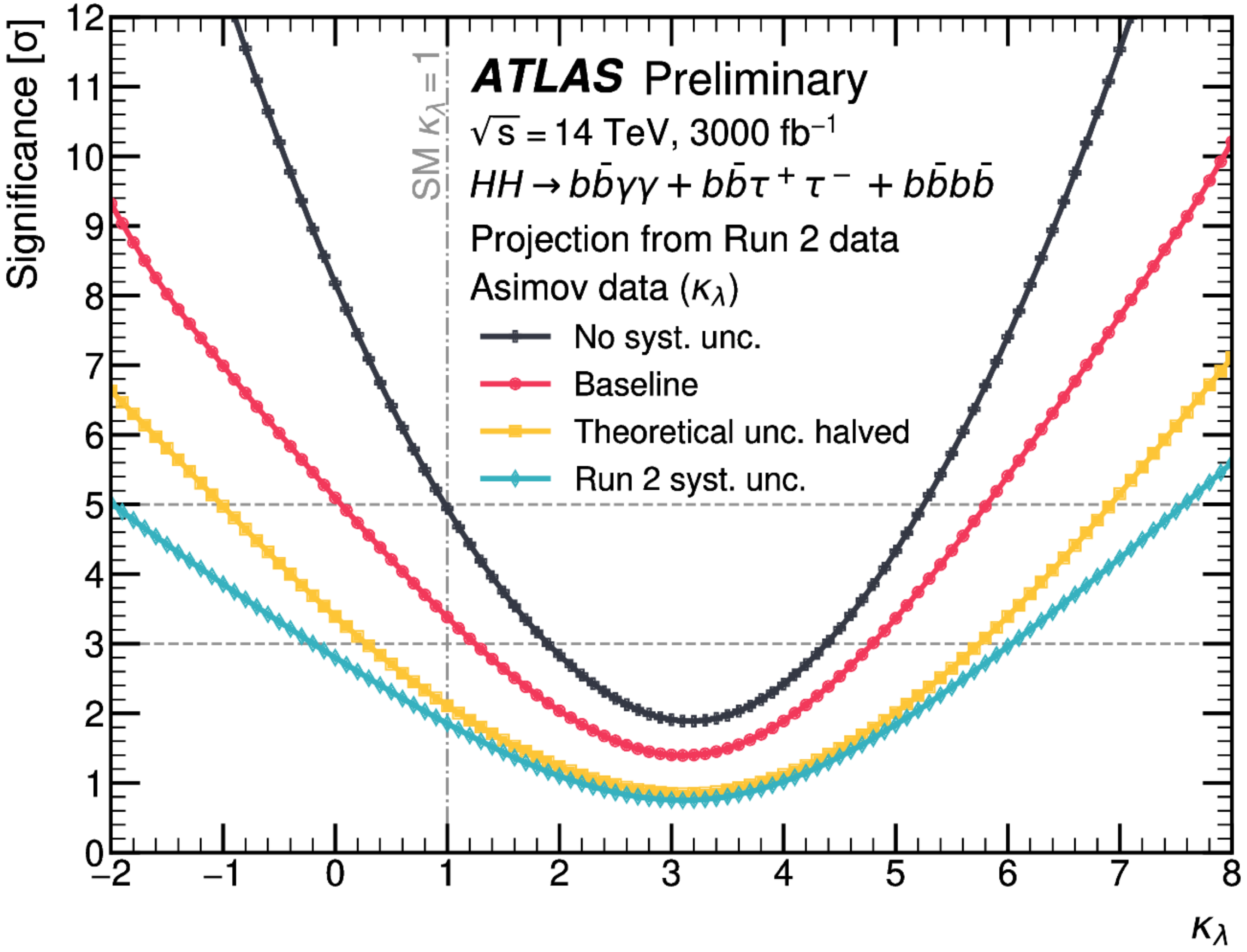
- Assuming Run 2 detector performance and expected reduction of systematics, **statistical evidence (3.4σ) is expected for SM HH ($\kappa_\lambda = 1$)** with $3000\ \mathrm{fb}^{-1}$.
    - κ_λ **constrained to** $[0.5,1.6]$ at 68% CL.
- **Reduction of systematic uncertainties** could bring us **close to discovery** (4.9σ with stat. only). And we still have to combine with CMS!





Updated HL-LHC projections for HH

ATLAS-PHYS-PUB-2022-053



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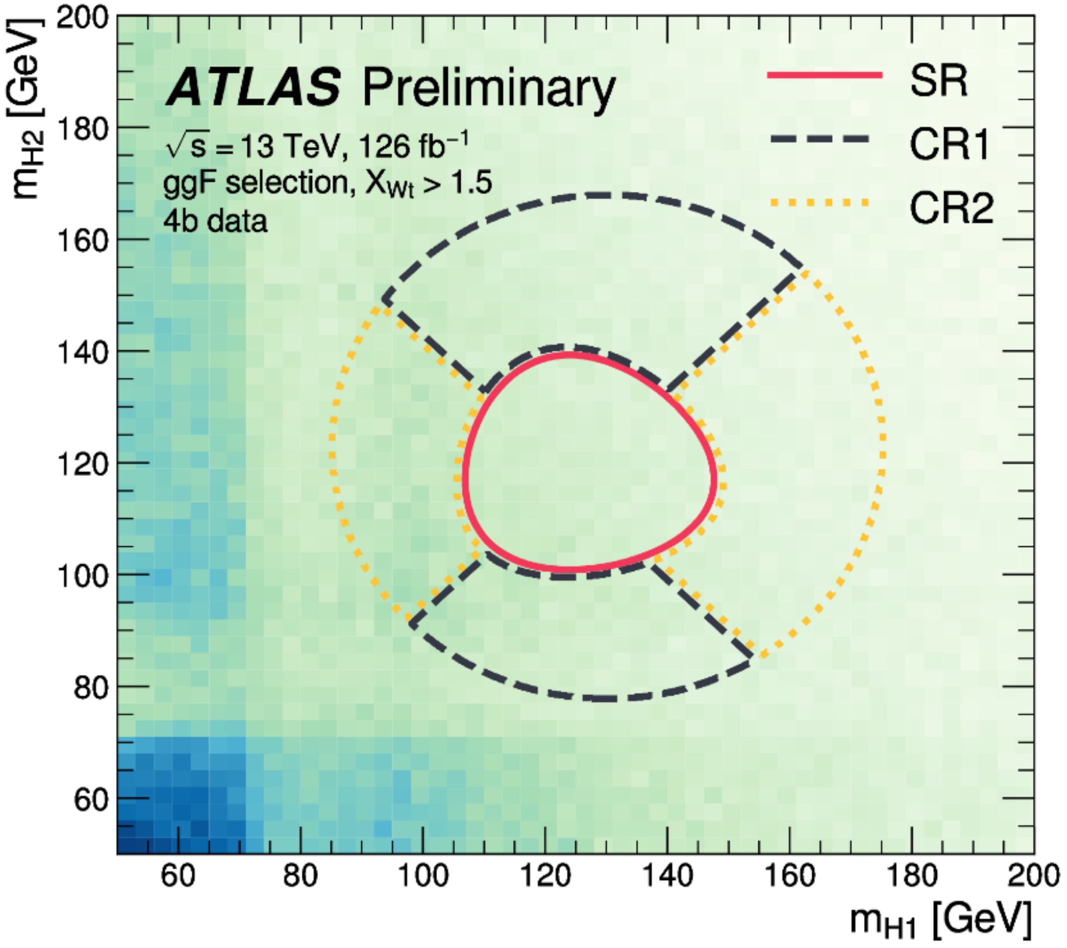
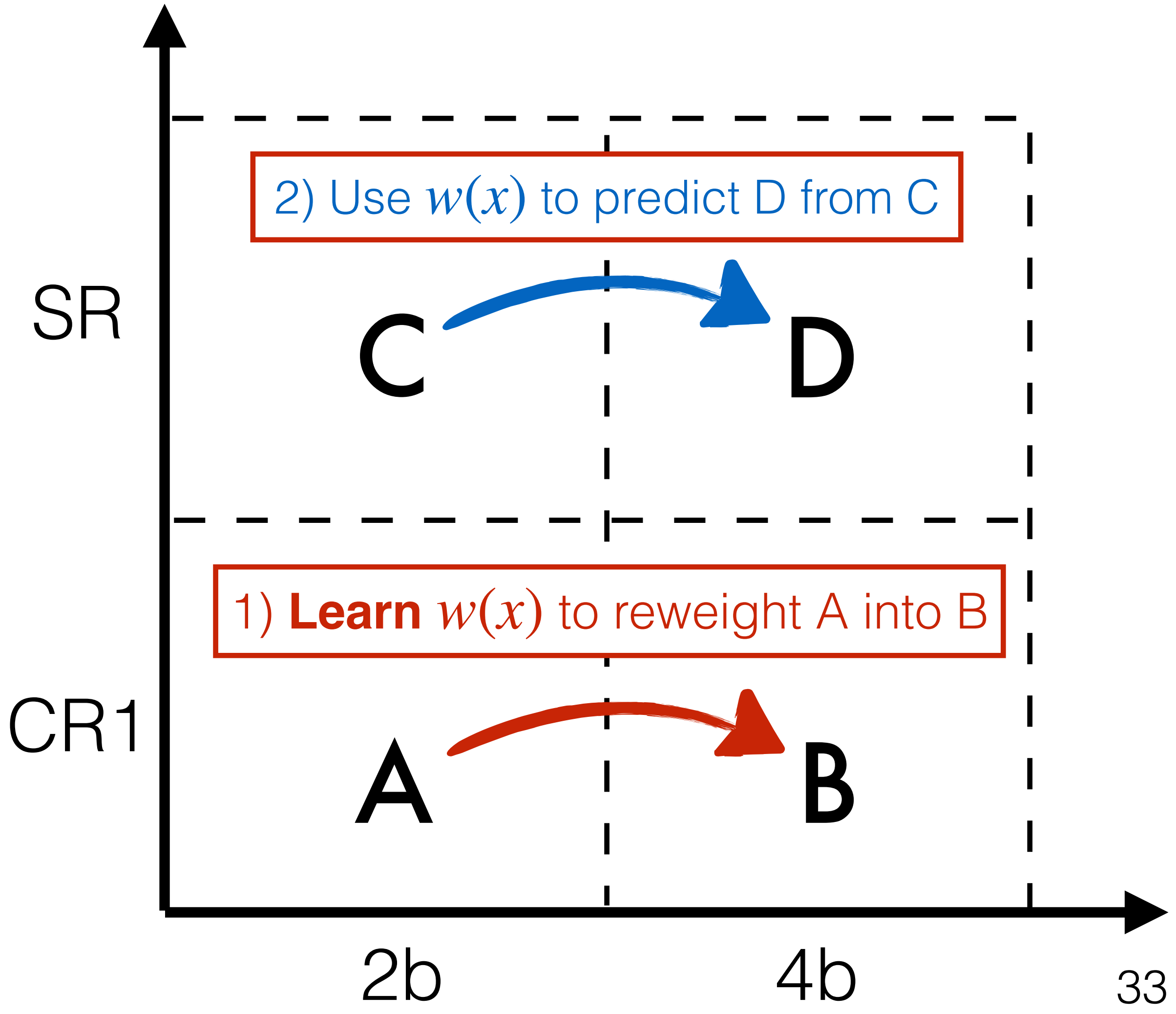
$HH \rightarrow b\bar{b}b\bar{b}$ analysis

Background estimation

- Background: QCD multijet (90%) and $t\bar{t}$ (10%) estimated using a **fully data-driven** method.
  - **Machine-learning algorithm learns weight $w(x)$**, where x are different event kinematic variables, to **reweight CR1- 2b into CR1-4b** events
  - $w(x)$ **applied to SR-2b** to obtain SR-4b background estimation.
- Alternative $w'(x)$ from CR2 used to estimate systematics uncertainties.





2) Use $w(x)$ to predict D from C

1) **Learn** $w(x)$ to reweight A into B

Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment

CAP 2024 [27-31 Ma7 2024]

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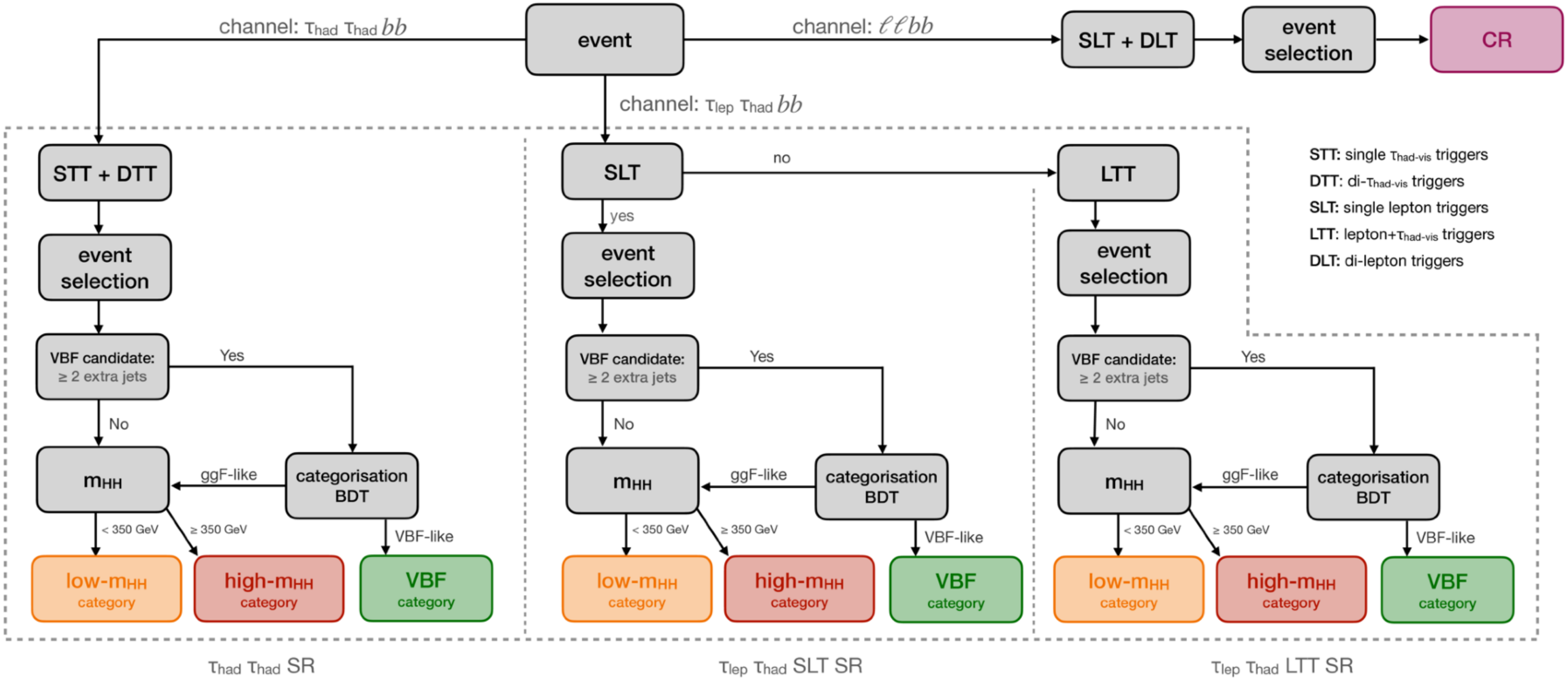
$HH \to b\bar{b}\tau\tau$ analysis

Analysis categories



event

channel: $\tau_{had}\tau_{had} bb$

channel: $\ell\ell bb$

channel: $\tau_{lep}\tau_{had} bb$

SLT + DLT → event selection → CR

STT + DTT → event selection → VBF candidate: ≥ 2 extra jets

SLT → yes → event selection → VBF candidate: ≥ 2 extra jets

SLT → no → LTT → event selection → VBF candidate: ≥ 2 extra jets

VBF candidate: Yes → categorisation BDT; No → m_{HH}

categorisation BDT: ggF-like → m_{HH}; VBF-like → VBF category

m_{HH}: < 350 GeV → low-m_{HH} category; ≥ 350 GeV → high-m_{HH} category

$\tau_{had}\tau_{had}$ SR

$\tau_{lep}\tau_{had}$ SLT SR

$\tau_{lep}\tau_{had}$ LTT SR

STT: single $\tau_{had\text{-}vis}$ triggers

DTT: di-$\tau_{had\text{-}vis}$ triggers

SLT: single lepton triggers

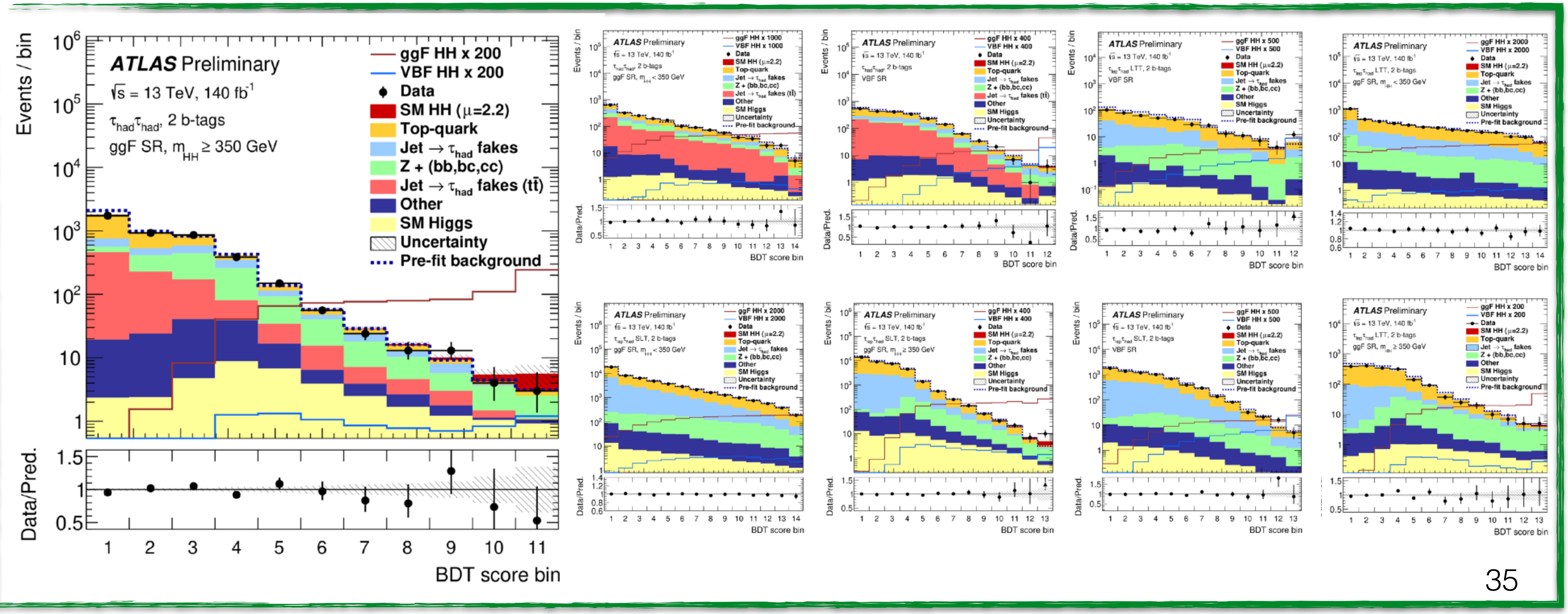
LTT: lepton+$\tau_{had\text{-}vis}$ triggers

DLT: di-lepton triggers

$HH \to b\bar{b}\tau\tau$ analysis

Background estimation and results

- Dominant backgrounds: $t\bar{t}$ and $Z(\to \tau\tau)$+bb/bc/cc)
- Final observation: **binned fit of MVA scores in all 9 categories**.
- **No significant excess** above SM prediction observed.

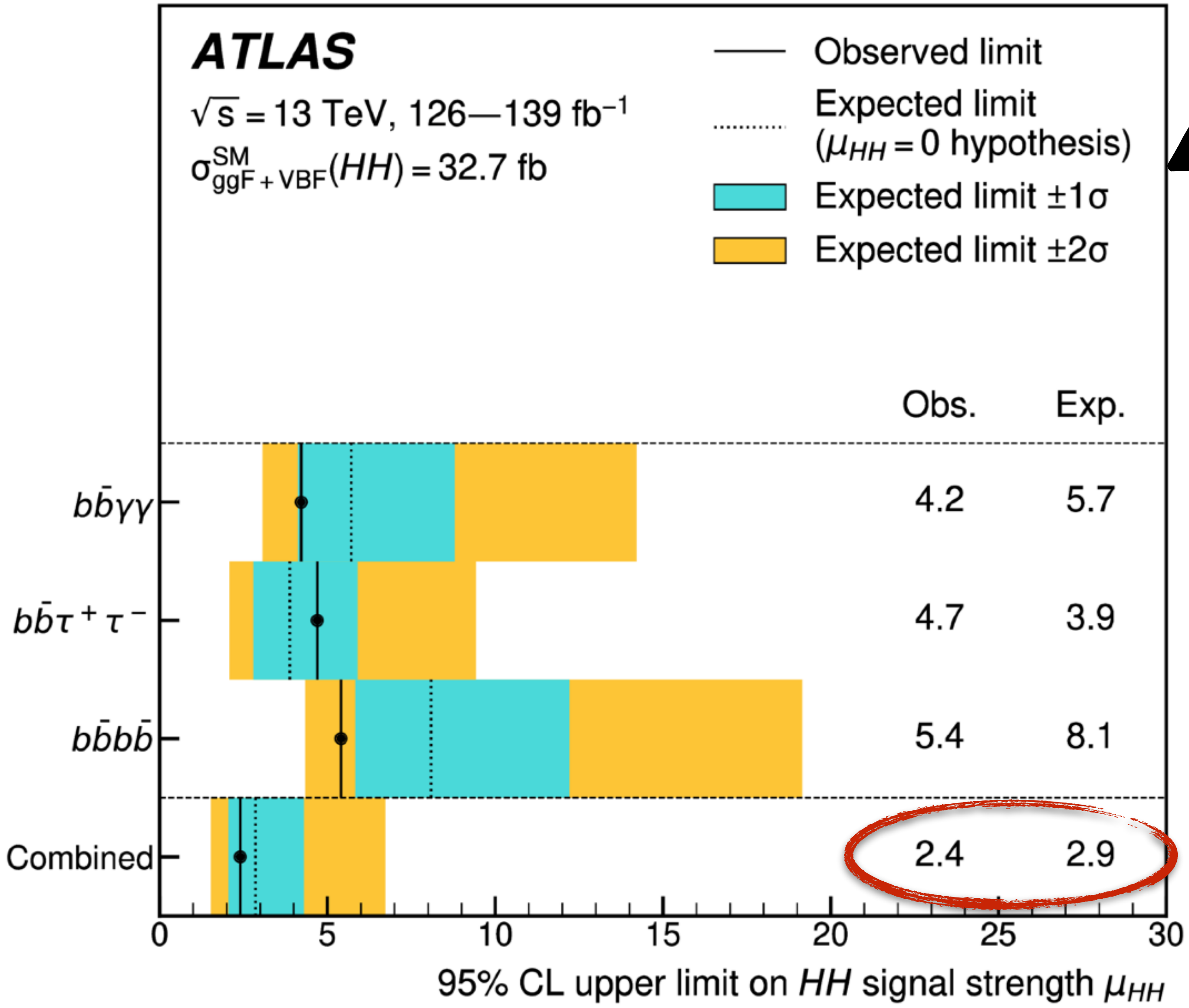


SM cross-section upper limits

Results

- Statistical **combination maximises sensitivity** to SM (and BSM) HH production

Phys. Lett. B 843 (2023) 137745



$$\mu_{HH} = \frac{\sigma^{\text{obs}}(pp \to HH)}{\sigma^{\text{SM}}(pp \to HH)}$$

Currently observing $\mu_{HH}^{95\%\text{ CL}} < 2.4$

Previous result (36 fb^{-1})

Expected: 26xSM
Observed: 20.3xSM

Expected: 15xSM
Observed: 12.5xSM

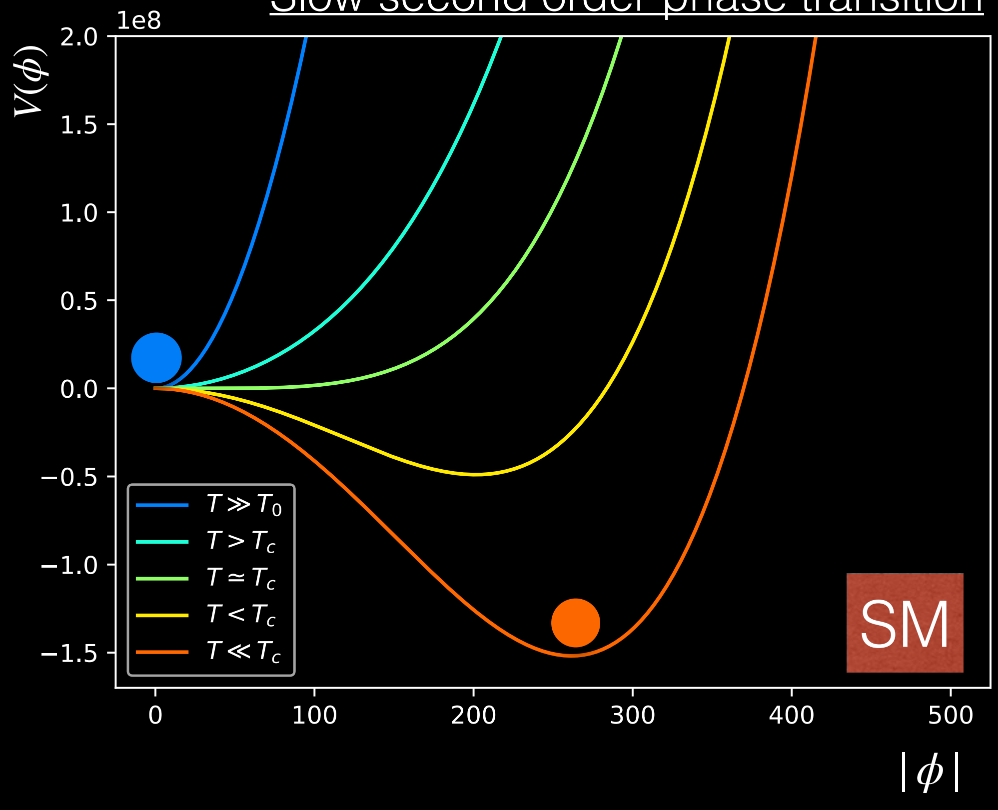
Expected: 20.7xSM
Observed: 12.9xSM

Expected: 10xSM
Observed: 6.9xSM

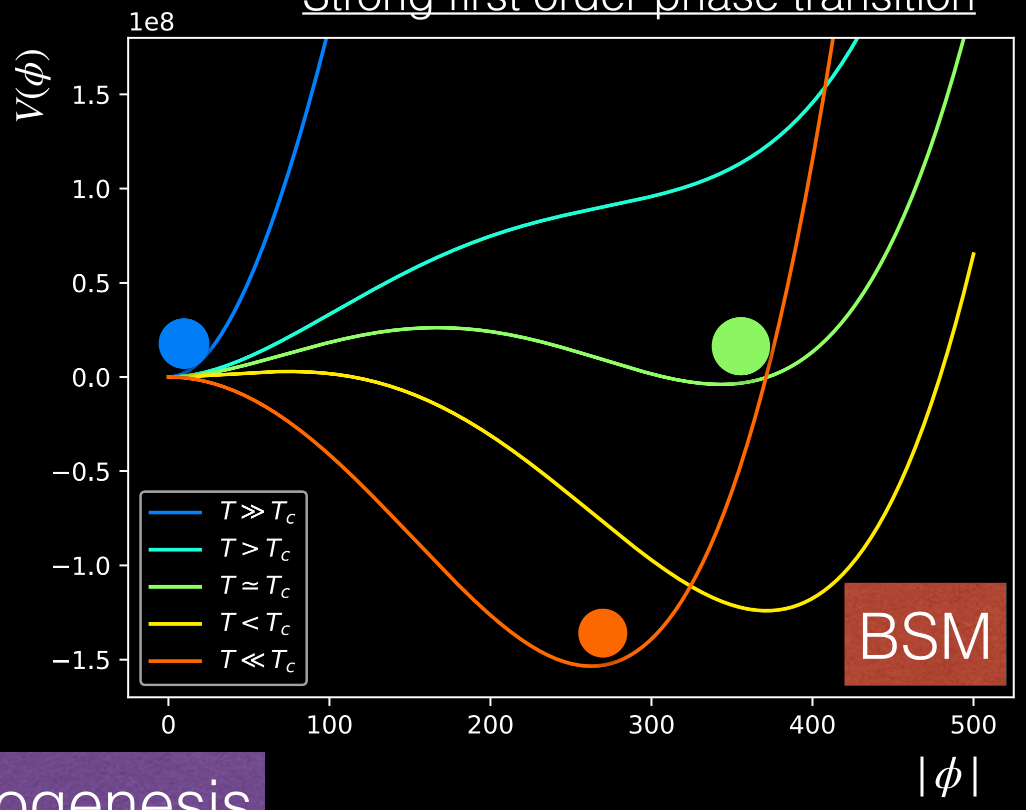
Large improvement (x3.5) thanks to **luminosity**, better **reconstruction** (b-jet, τ) and **analysis improvements**

Getting very close to the SM ($\mu_{HH} = 1$)

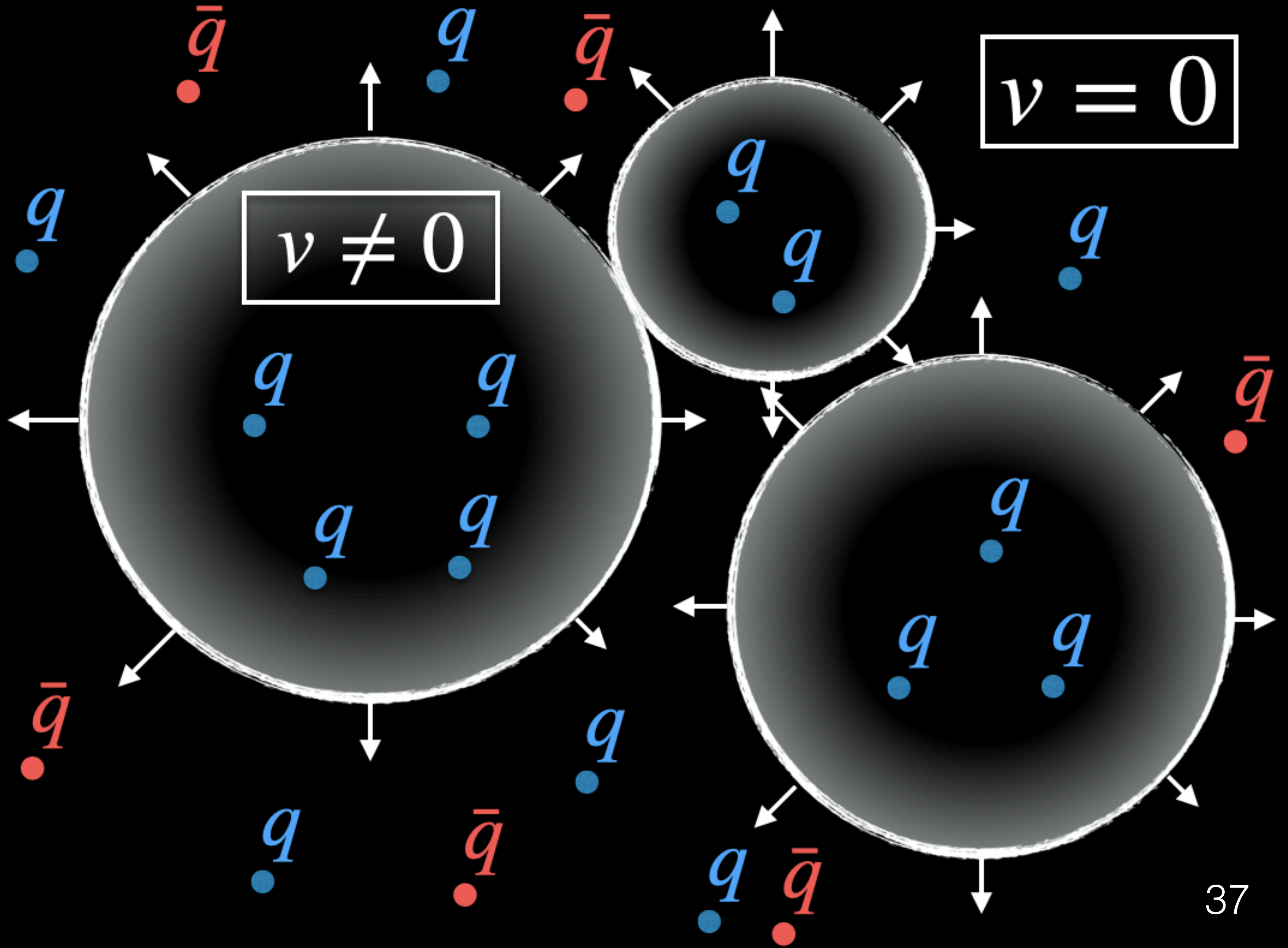
Slow second order phase transition



Strong first order phase transition



EWK baryogenesis



- **BSM effect in the Higgs potential could explain the matter-antimatter asymmetry** of the universe.
    - BSM physics acting on the Higgs potential would enable EWK bubble nucleation.

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$HH \to b\bar{b}\gamma\gamma$ analysis

Additional material

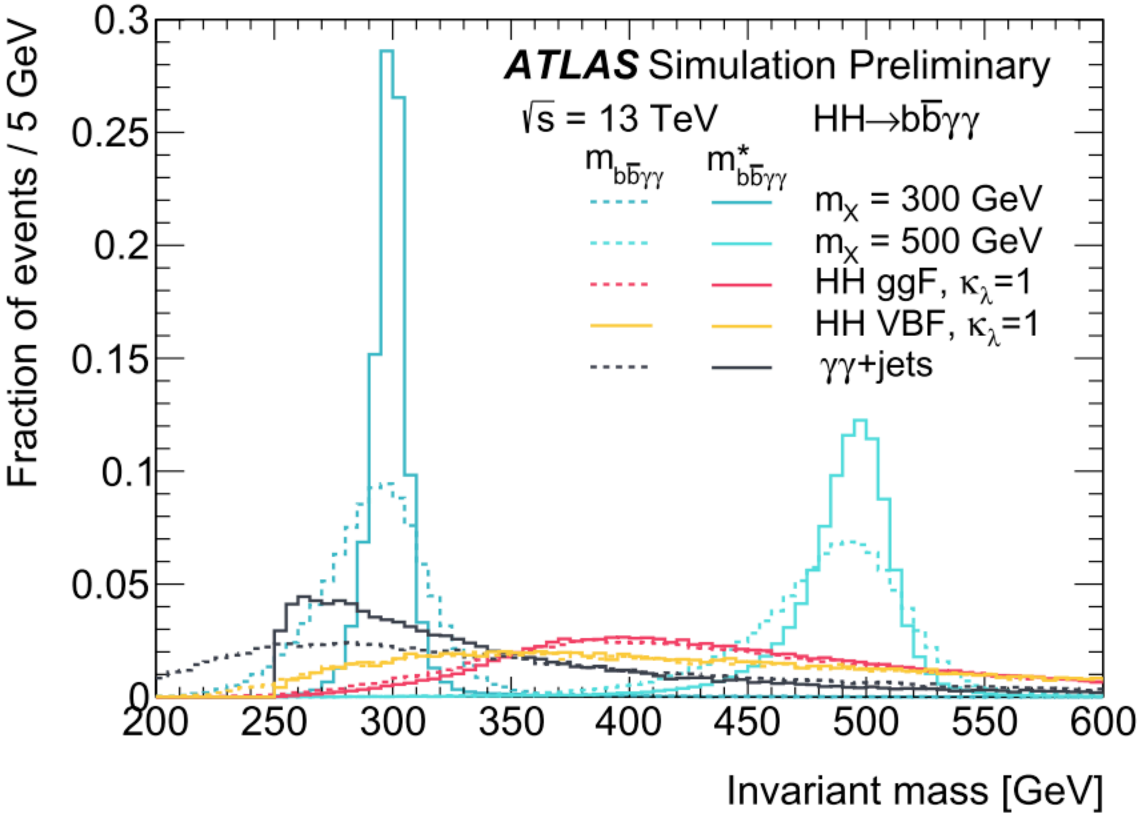

Figure 4: Reconstructed four-body mass for $m_X = 300$ GeV and $m_X = 500$ GeV resonant signal benchmarks and for the $\gamma\gamma$+jets background. Dashed lines represent the distribution of $m_{b\bar{b}\gamma\gamma}$ while solid lines represent the distribution of $m^*_{b\bar{b}\gamma\gamma}$, defined in Section 4.2.1. Distributions are normalized to unit area.

Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment
CAP 2024 [27-31 Ma7 2024]

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Physics department
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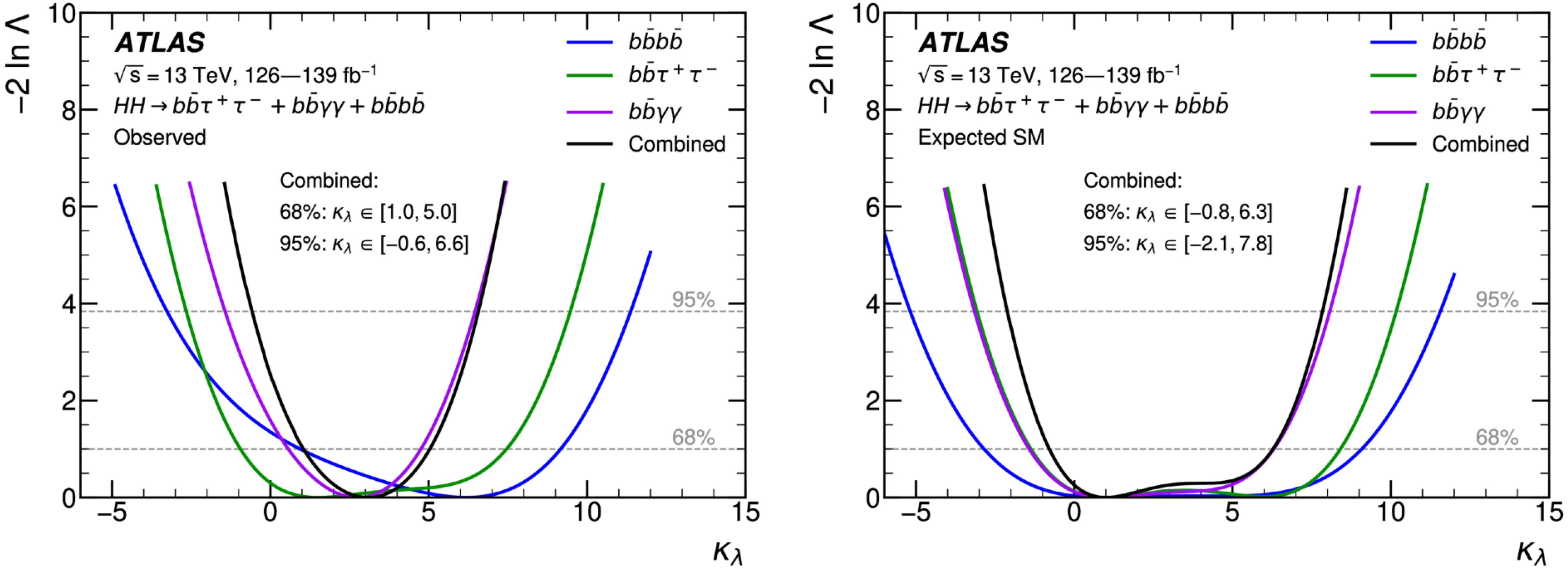
HH combined and separate likelihoods

arxiv:2211.01216

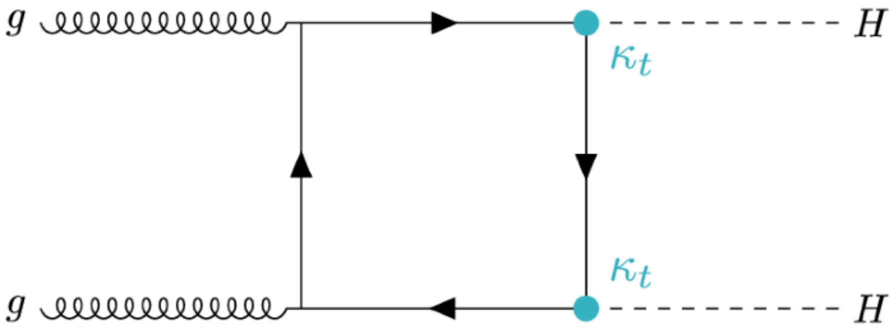


Single-Higgs constraints to κ_λ and κ_t

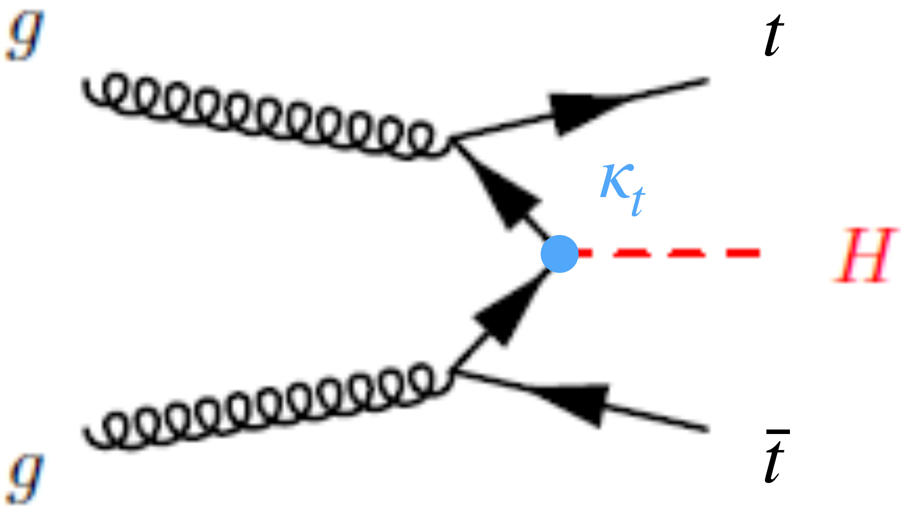
Results

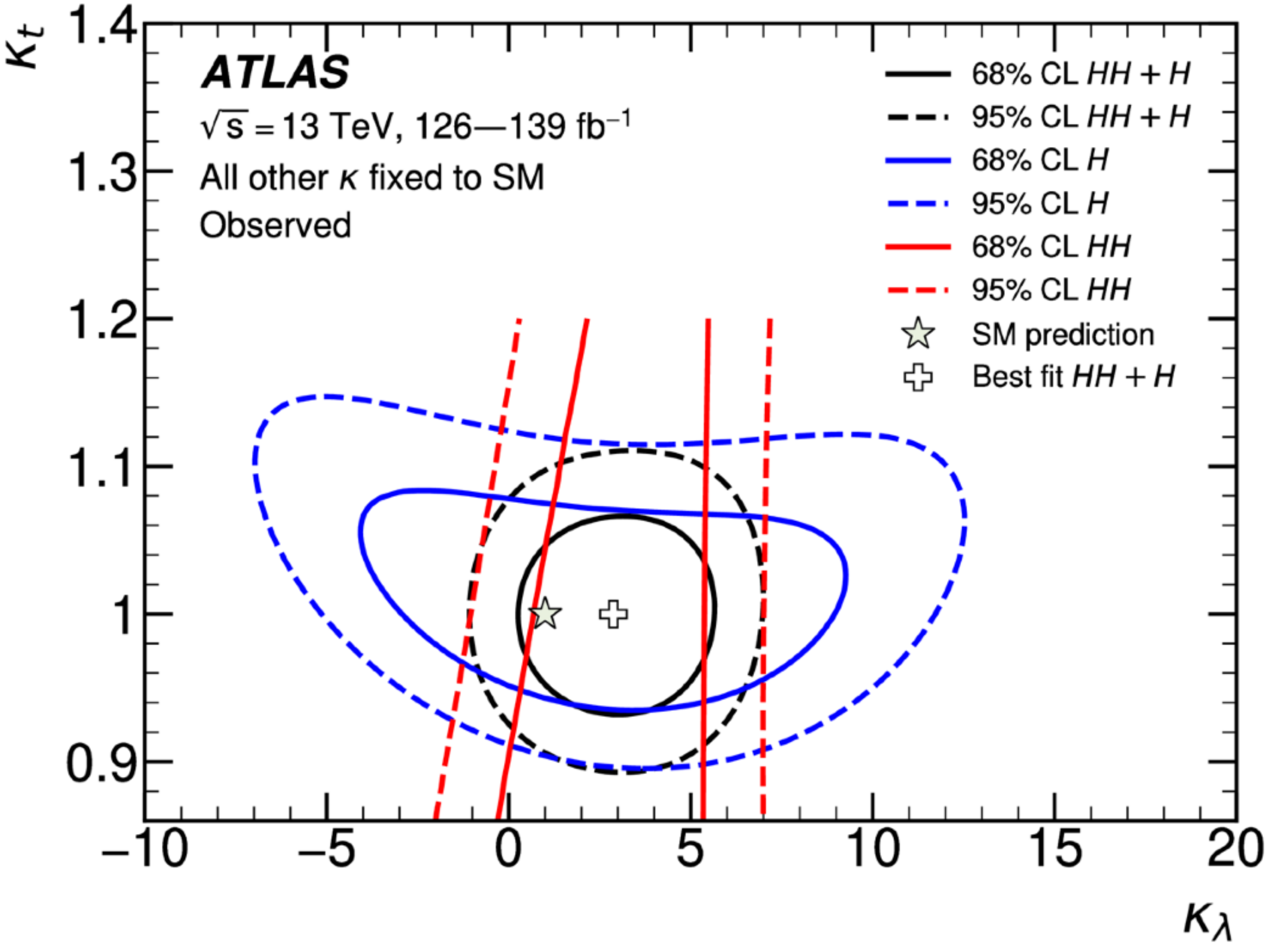
- **Combination with ttH** also **allow to constrain HH box-diagram effects** via direct measurement of κ_t

HH box diagram



ttH

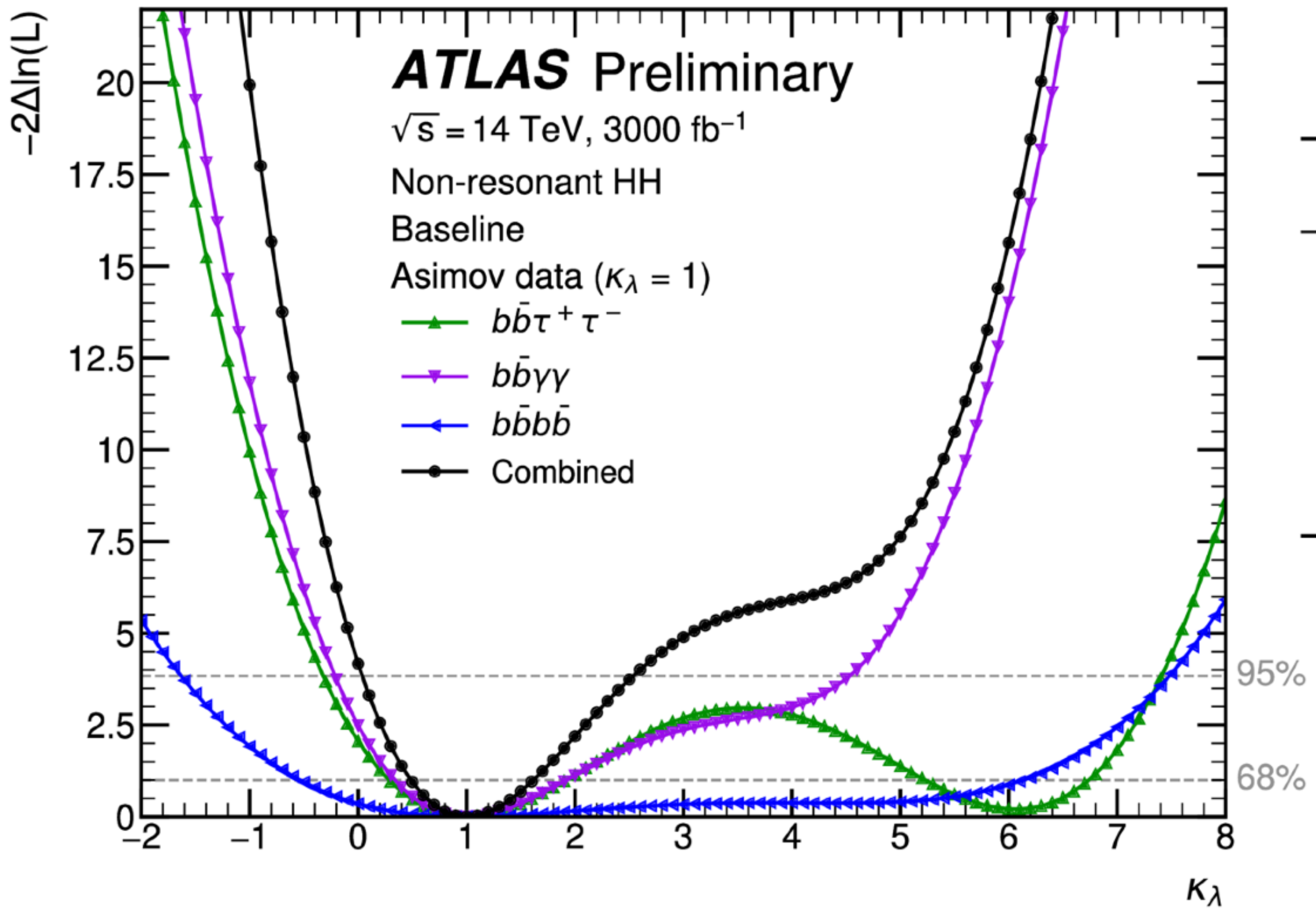




Updated projections for HL-LHC

ATLAS-PHYS-PUB-2022-053

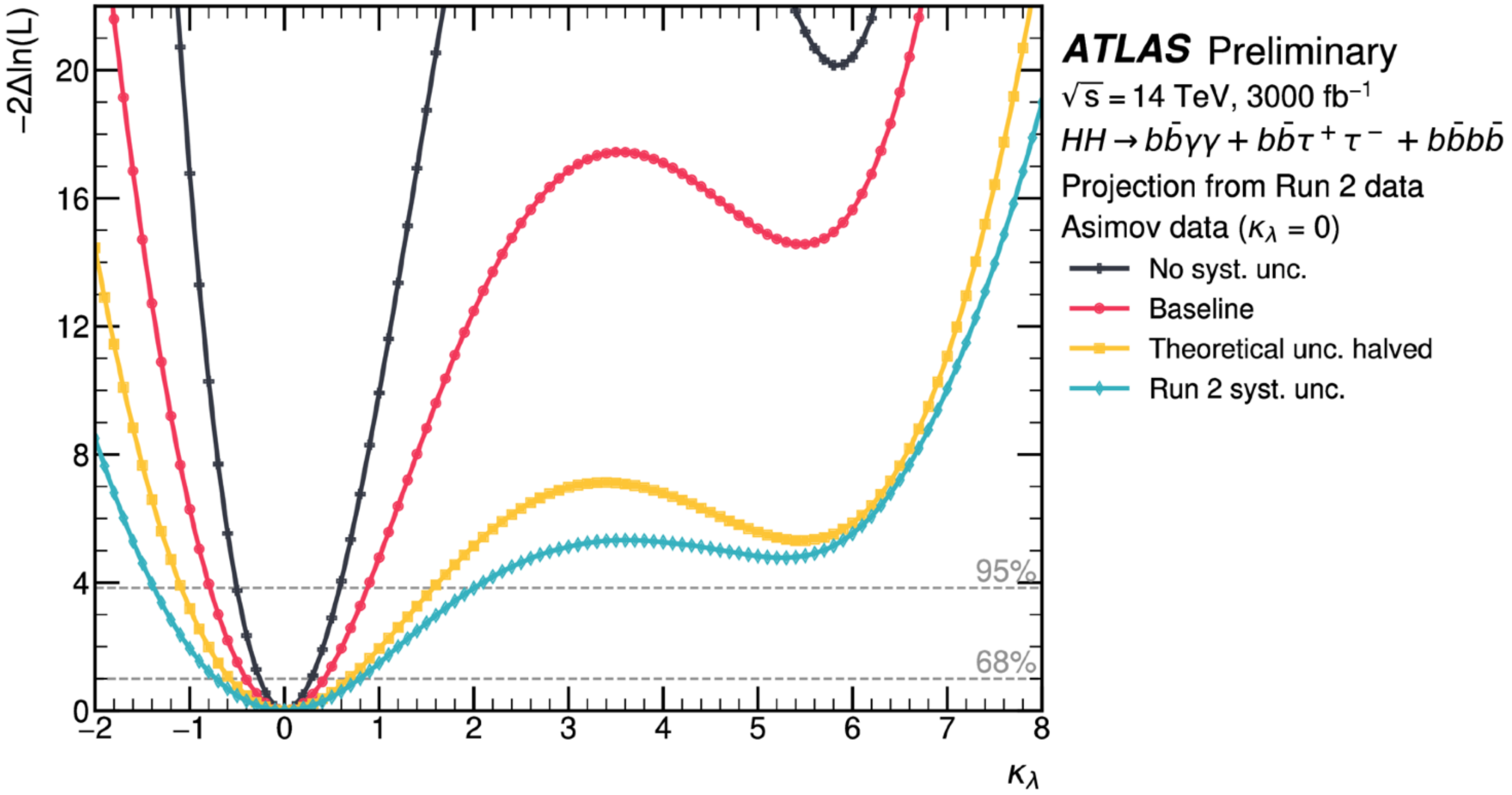
	Significance [σ]				Combined signal strength precision [%]
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	
No syst. unc.	2.3	4.0	1.8	4.9	$-21/+22$
Baseline	2.2	2.8	0.99	3.4	$-30/+33$
Theoretical unc. halved	1.1	1.7	0.65	2.1	$-47/+48$
Run 2 syst. unc.	1.1	1.5	0.65	1.9	$-53/+65$



Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Updated projections for HL-LHC

ATLAS-PHYS-PUB-2022-053



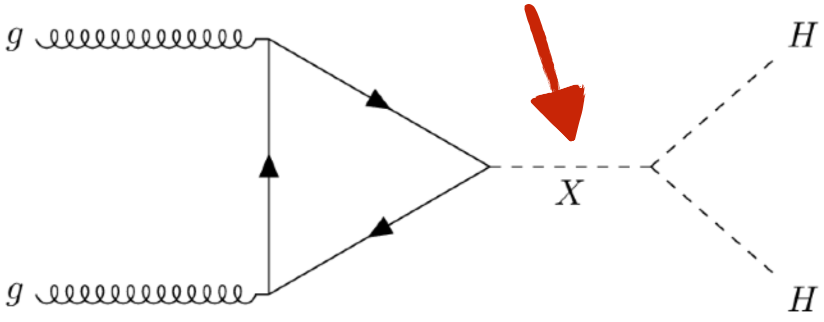
Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	$[-0.3, 0.3]$	$[-0.5, 0.6]$
Baseline	$[-0.4, 0.4]$	$[-0.8, 0.9]$
Theoretical unc. halved	$[-0.6, 0.7]$	$[-1.1, 1.6]$
Run 2 syst. unc.	$[-0.7, 0.8]$	$[-1.4, 2.0]$

Resonant interpretation

Resonant upper limits

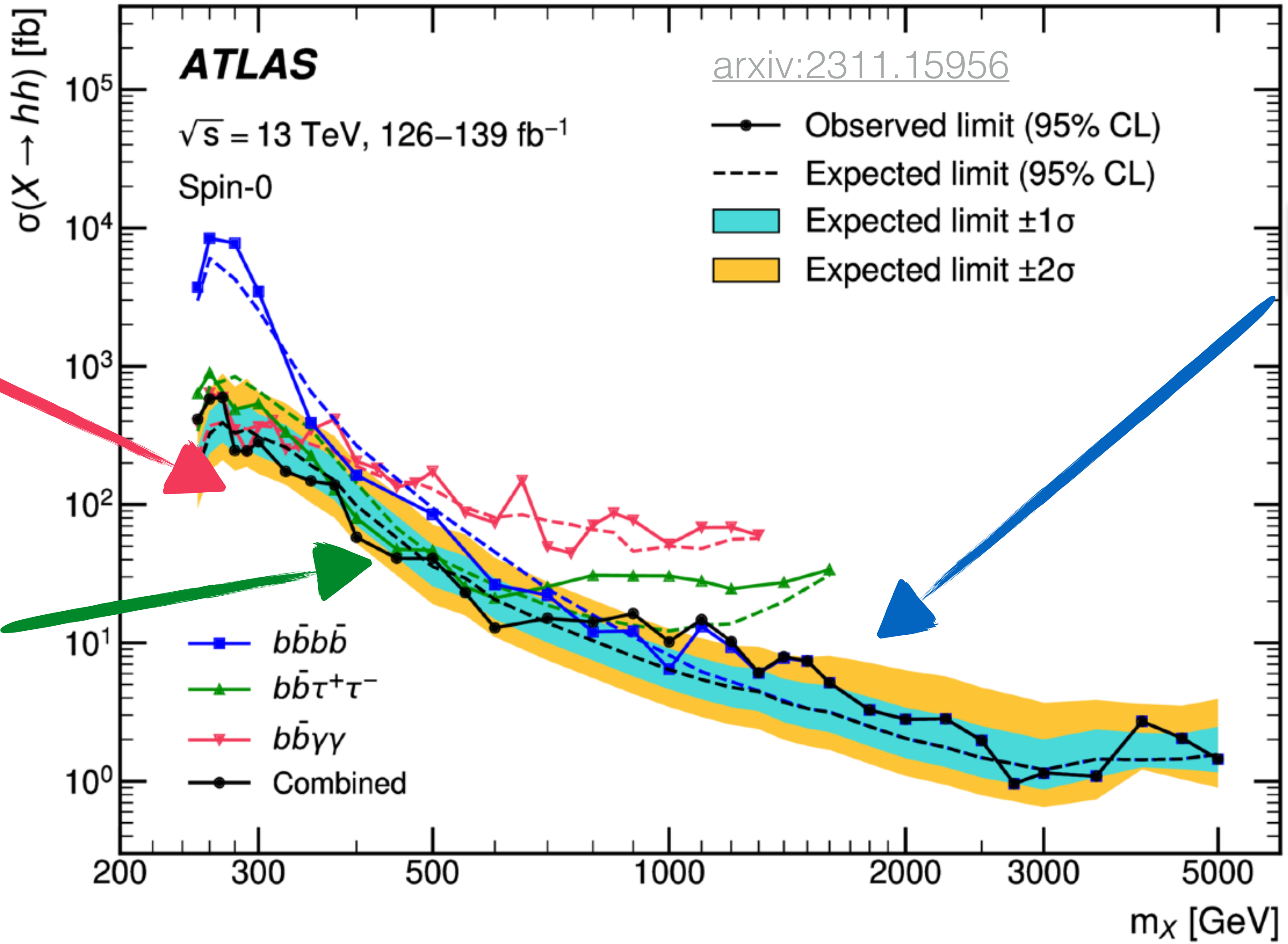
- BSM models also predict **possible heavy resonances decaying to HH**
  - Re-optimised analyses to target these scenarios.
- Complementarity between channels allow to obtain **optimal exclusion** across m_X.
- **No statistically significant excess** found: largest excess at $m_X = 1.1$ TeV, with local (global) significance of 3.2σ (2.1σ).

Heavy spin-0 resonance



$b\bar{b}\gamma\gamma$ dominated

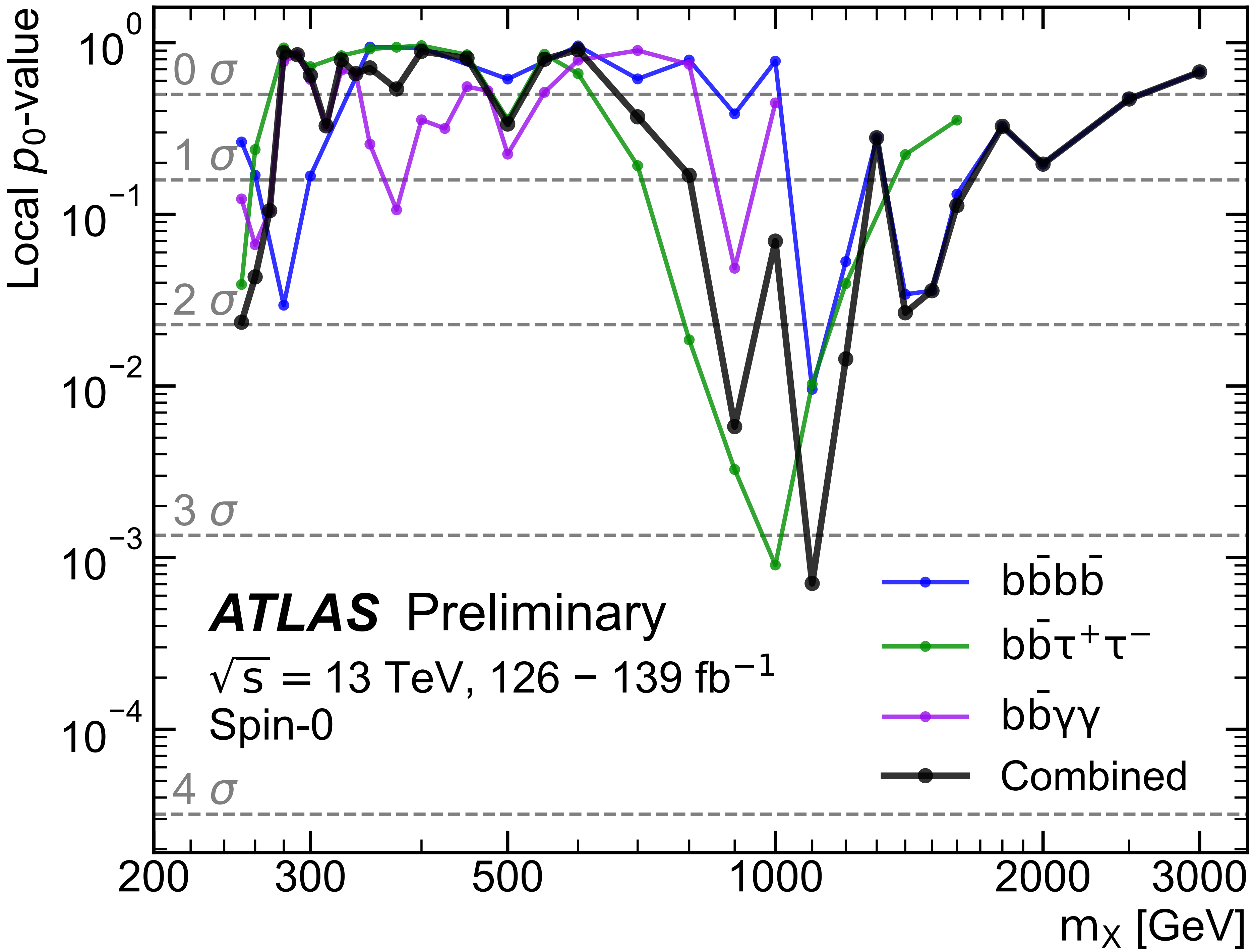
$b\bar{b}\tau\tau$ dominated



$b\bar{b}b\bar{b}$ dominated

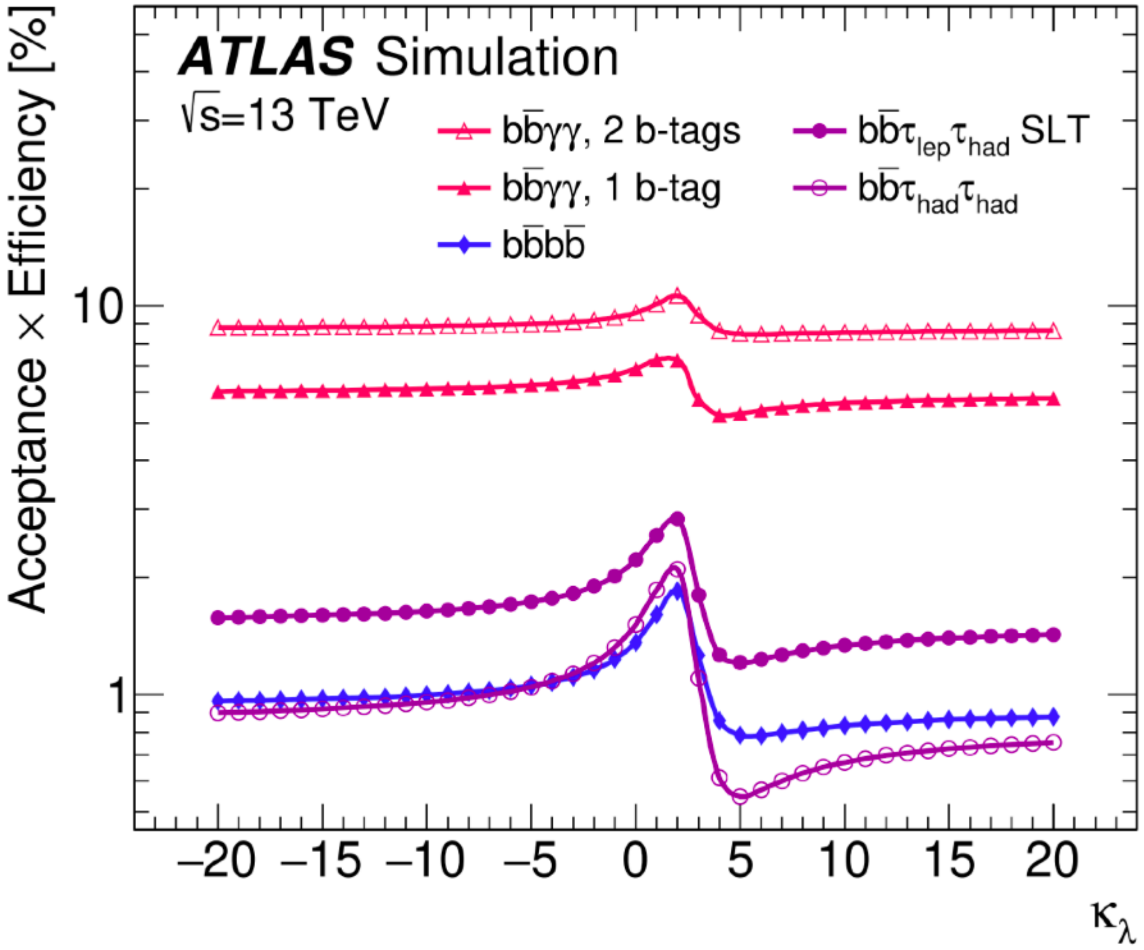
Combination p-value

Additional material (resonant)

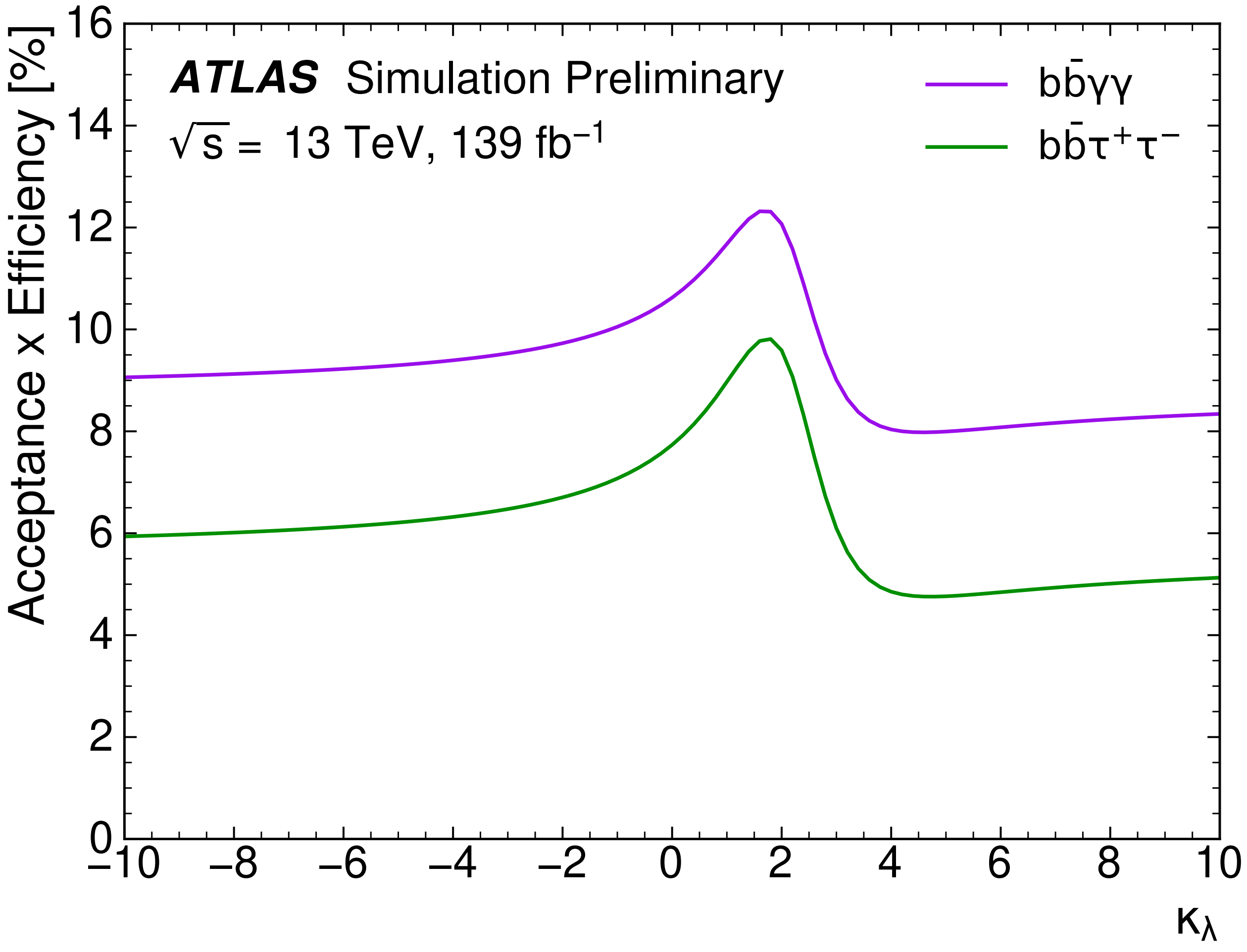


Combination acceptances vs κ_λ

Partial Run 2 combination ($36\ \text{fb}^{-1}$)

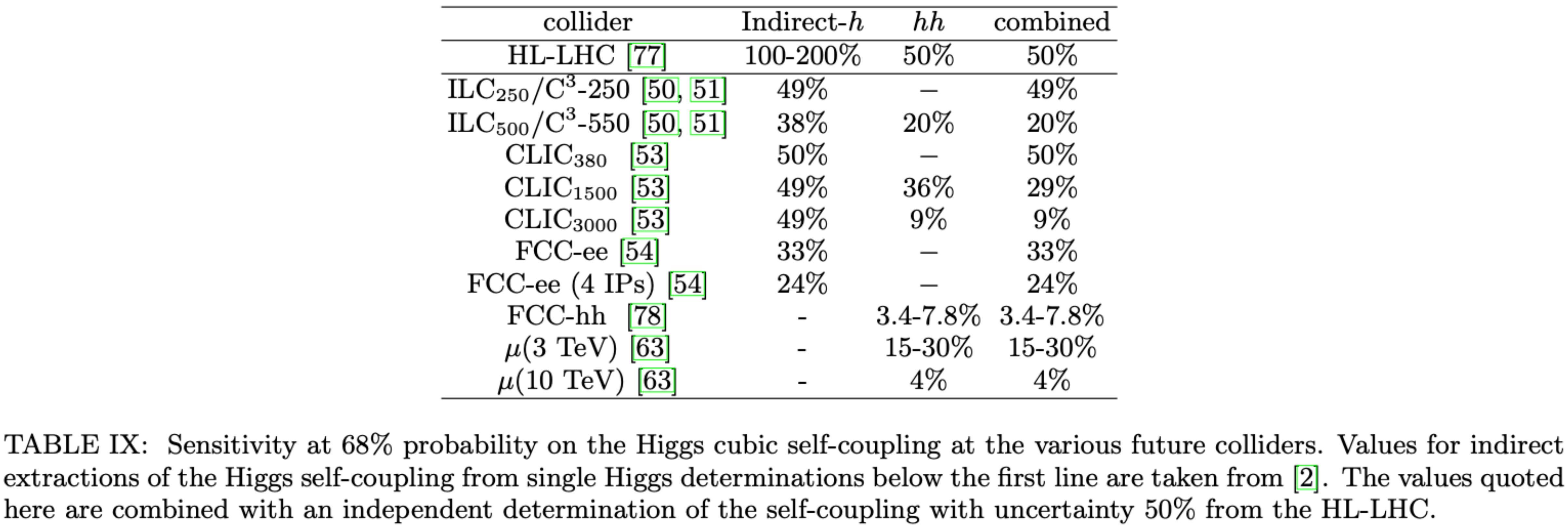


Full Run 2 combination



κ_λ constraints at future colliders

arxiv:2209.07510



collider	Indirect-h	hh	combined
HL-LHC [77]	100-200%	50%	50%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250 [50, 51]	49%	–	49%
$\mathrm{ILC}_{500}/\mathrm{C}^3$-550 [50, 51]	38%	20%	20%
CLIC_{380} [53]	50%	–	50%
CLIC_{1500} [53]	49%	36%	29%
CLIC_{3000} [53]	49%	9%	9%
FCC-ee [54]	33%	–	33%
FCC-ee (4 IPs) [54]	24%	–	24%
FCC-hh [78]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [63]	-	15-30%	15-30%
μ(10 TeV) [63]	-	4%	4%

TABLE IX: Sensitivity at 68% probability on the Higgs cubic self-coupling at the various future colliders. Values for indirect extractions of the Higgs self-coupling from single Higgs determinations below the first line are taken from [2]. The values quoted here are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.